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· WEAL

STUDY AND INVESTIGATION OF SPECIALIZED

ELECTRO-ACOUSTIC TRANSDUCERS

for

VOICE COMMUNICATION IN AIRCRAFT

Contract AF33(616)-3710 Phase II Final Report

January 1960

Western Electro-Acoustic Laboratory, Inc.

Los Angeles, California *941 400*

FOREWORD

ABSTRACT

The objective of this program was to discover communications
transducers which would permit reduction in the encumberance
of combined communication, protection and respiration equipment
used in high altitude, long range missions.

Phase I of the program was previously reported in February 1959.
This phase disclosed several new techniques for the projection and
reception of voice communication which promise less weight and
bulk of transducers and defined the limits of noise tolerance of
each technique.

Phase II of the program, reported herein, explored the more
promising transducers and coupling means. In particular, the
limits of expected noise in future aircraft and spacecraft were
studied and predicted. The use of bone conduction for reception
was discarded. Experimental adaptations of the AIC/10 system
employing the forehead microphone, tooth accelerometer microphone,
horn-coupled receiver, direct coupled miniature receiver, and
direct radiating loudspeaker, were assembled and their performance
measured to define the limits of their utility in noise and their long
duration comfort tolerance. Specifications for prototype development
are provided. Evaluation techniques have been greatly improved in
speed, accuracy, and reproducibility.

If pursued, these advances can go far toward solving the immediate
problems and meeting foreseeable future needs.

TEXT OUTLINE

1.0 INTRODUCTION

The inception of this program was responsible to the forcible realization that the encumbrance of combined communication, protection and respiration equipment was such that the operational effectiveness of flyers was hampered to a critical extent on long range missions. At the beginning of the program continuous wearing of headgear was limited by pain tolerance to 3 to 8 hours. At that time a tolerance duration of 40 hours was stated as an objective.

During the course of this program the boundaries of missions have literally exploded and only limitless space itself now encompasses the potential military mission. Furthermore, we have been subject to major vascillations in concept: at one turn the large manned airplane seemed doomed to sudden extinction as we viewed with over-optimism the progress of missilry and we imagined the grounded human as director of obedient destructive or defensive semi-automatons. Then came the disquieting realization that the dependability and precision of the automatons was not and could not be expected to be adequate, and that man's ability to guide, correct, observe and correlate his mechanical assistants could not be superceded. And finally, in a return to realism, came the recognition that we were a long way from doing without the manned weapons of the present.

And so the communications problems which we faced at the beginning of our program may now be viewed at the present phase:

A. Their solution was essential to the continuing effectiveness of the military aircraft we now have and are likely to be dependent upon for a considerable period as technology advances.

B. As our mission boundaries enlarge into unlimited space, man will be an essential and controlling factor in the space environment, and his usefulness and effectiveness there will be, as in all his historic past, utterly dependent upon communications: language, voice and hearing, received and transmitted. Missions near the earth will be of shorter duration, higher speed, and higher noise level. Space missions will probably be less noisy, but their duration will make the 40-hour limit appear as a moment. And man's very presence and sustainance will be utterly dependent upon the solution of the problems and continuity of the studies described in this program.

Phase I of the program has disclosed potential advances which go far toward solving the immediate problems and meeting future demands. Phase II has further explored the more promising transducers and coupling means, proved their value, and provides specifications for prototype development. Evaluation techniques have been greatly improved in speed, accuracy and reproducibility.

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2.0 OBJECTIVES

Improvements are desired in voice communication equipment which will:

1. Decrease the size, weight and discomfort associated with equipment which must be worn on or about the head of the flyer.

2. Achieve as good as or better intelligibility in aircraft noise than that presently provided by the AN/AIC-10 interphone equipment.

3. Be readily adaptable for use with the AIC-10 system.

4. Be compatible with other essential flight functions such as auxiliary respiratory equipment, vision and mobility requirements, accelerations incurred during maneuvers, wearability without unreasonable discomfort for 40-hour duration, the gradually increasing noise environment within aircraft.

3.0 PROGRAM OUTLINE

The following outline is based upon "Specific Recommendations for Phase II of the Program," as given in Contract AF33(616)-3710 Final Report, February 1959.

1. Define and project probable future noise exposure due to (a) increased sustainer propulsion, (b) assisted takeoff, (c) greatly increased speed and altitude, (d) ventilating equipment in cockpits and flying suits.

2. Continue the development of the tooth accelerometer microphone in relation to (a) refinement of mounting, (b) wearability, (c) adaptation to the AIC-10 system.

3. Define the prospective utility of the forehead microphone in relation to projected aircraft interior noise spectra.

4. Define projected helmet use conditions in relation to noise protection, mobility, capsule enclosure.

5. Make a carefully controlled measurement of the relative aural thresholds in response to sound pressure on the forehead as compared with sound pressure at the entrance to the ear canal.

6. Apply the measurement from (5) to an analysis of the bone conduction driver unit (presumably dynamic inertial type) to determine the feasibility of adequate excitation with reasonable power for high level speech reception.

7. Repeat critical measurements and study the utility of the horn coupling from a receiver unit to the general vicinity of the ears without head contact.

8. Study in experimental model form the utility of a small loudspeaker radiating directly into the interior of the flying helmet without head contact.

9. Define the utility of an externally mounted loudspeaker with special attention to the problem of ambient noise limitations, need for sidetone, and propensity for acoustic feedback.

10. Evaluate the relative intelligibility of standard PB words as compared with the special CVC words used in Phase I of the program.

11. Recheck the relative levels of speech as measured by integrated rms, long-time average, peak reading, and VU meter.

12. Assemble in experimental model form and evaluate, in as nearly as possible operational conditions, complete systems consisting of useful combinations of the

following projection and reception units: microphones: tooth accelerometer, forehead accelerometer, exposed noise-cancelling (M55). Receivers: coupling horns inside helmet, loudspeaker inside helmet, forehead bone conduction receiver, external loudspeaker

4.0 FINDINGS

The findings of the program divide logically into five categories:

1. Communication system capabilities in manned compartments of very high performance aircraft and space vehicles.
2. Microphone development
3. Reception system development.
4. Miscellaneous studies
5. System articulation testing.

4.1 Communication System Capabilities in Manned Compartments of Very High Performance Aircraft and Space Vehicles

4.1.1 Summary

This section contains predictions of the maximum noise environment in which certain transducers will yield satisfactory communication.

The predicted maximum noise spectra external to manned compartments in very high performance aircraft and space vehicles for both propulsion system noise and aerodynamic noise are discussed in Appendix 1 and Reference 1. These spectra were translated into an internal noise environment for several types of assumed compartment structures. The capabilities of microphones, headphones and loudspeakers in noise fields are also reported in Reference 2. Hence, the communication systems which will yield satisfactory articulation scores in high performance aircraft may be determined.

Similarly, attenuation requirements for ear protection devices may be determined for hearing loss and comfort criteria.

4.1.2 Maximum Internal Noise Spectra

High Performance Manned Aircraft

Figure 1 gives the predicted internal noise within the canopy of a high performance manned aircraft. The figure is developed from the external noise for takeoff, the external noise at high dynamic pressures, and the noise reduction for a typical bubble canopy.

Manned Space Vehicle

Figure 2 gives a similar presentation for the launch and re-entry phases of a manned space vehicle. Two types of attenuating structures are assumed: a heavy-walled capsule of 3/4-in. copper, and a lightweight double-walled structure. These are described more fully in Appendix 1.

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4.1.3 Communication System Capabilities

Prediction Scheme

In reference 2 the capabilities of speech reception and projection systems were given. Their performance was based upon articulation tests performed in the jet noise spectrum shown in Figure 3. This spectrum was derived from data reported in WADC TN 56-411. Unfortunately, the noise spectra as shown in Figures 1 and 2 differ from the jet test spectrum. Hence, a technique for extrapolation is necessary. Also included in this figure are military criteria for acceptable noise levels in military aircraft for cruise and short duration noise, drawn from Reference 4.

We have used the weighted noise level of Pickett and Kryter from Reference 3. The overall sound pressure level for each octave band listed below is multiplied by the weighting factor given.

Band	Weight
300 – 600 CPS	1
600 – 1200 "	1
1200 – 2400 "	2
2400 – 4800 "	2
4800 – up	1

The total of these weighted measures is then averaged by dividing by 7, the number of weights. For example, for the jet test spectrum of Figure 3 the weighted noise level is 104 db. For the cruise condition of Figure 1 the weighted noise level is 103 db.

This comparison may be an over-simplification, but the inaccuracies are probably no worse than those in the prediction of the external noise environment of the canopy or the capsule attenuation.

Results

The results of Reference 2 and the weighted noise levels obtained from Figures 1 and 2 are combined in Figures 4 and 5. The transducers described are illustrated schematically in Figures 6 and 7. The vertical lines indicate the weighted noise levels for the maximum noise conditions. Any system which lies to the right of a particular noise level will yield at least a 90% sentence articulation score.

For example, in Figure 4, choose the noise anticipated, such as space vehicle, re-entry, single wall. Following the vertical line down we find that at a normal speaking effort the seven systems (9 – 15) would not be acceptable since their slanted lines lie to the left of the noise level. At a raised speaking effort systems 11 – 15 are unacceptable. For short periods of time a "very loud" effort could be tolerated. For long periods, such as cruise, "raised effort" should not be exceeded. Conversely, for a

given microphone, the maximum noise level for a 90% sentence score may be determined.

The same general procedure is followed in Figure 5. If the bar extends to the right of the noise level, then the system will yield at least a 90% score. The unshaped portion of the bar indicates the maximum long time capability of the system, the length in general being limited by the hearing damage risk criterion (see Figure 8). The extension of this bar, indicated by shading, indicates that the system can be used at higher noise levels if the damage risk criterion is neglected and the system is limited only by the power handling capacity of the transducer or ear overloading. Ear overloading will occur when the noise or speech peak levels at the ear exceeds 125 db overall. The actual lengths of these bars are determined from a knowledge of the following factors: (1) the real ear response and power handling capacity of the transducer; (2) the real ear attenuation of the ear protection; (3) an articulation index computation. (These procedures are described in Reference 2.)

Discussion

The above results indicate that the present AIC-10 components should yield satisfactory performance in anticipated space vehicles and high performance aircraft. The proposed exposed forehead microphone appears to be marginal under certain conditions; however, more recent data using an inertial unit indicates that it may yield 90% sentence intelligibility in a 5 - 10 db higher noise field than shown in Figure 4.

The alternative speech reception systems such as horn coupling and external loudspeaker, all appear to be capable of 90% sentence intelligibility in the noise fields anticipated.

4.1.4 Ear Protection Requirements

Noise Criteria

Noise criteria have been developed to specify human tolerance to noise exposure. Separate noise criteria are necessary for the following general areas, as shown in Reference 5.

Impairment of Human Hearing

Negligible damage to hearing will occur if the noise exposure is below certain levels. These levels are known as damage risk criteria (DRC). They are based upon exposure over an 8-hour workday over a lifetime. Two such criteria are given in Figure 8. Hearing protection is generally considered mandatory when the noise exceeds the 95 db DRC and is recommended if the noise exceeds the 85 db DRC.

Interference with Human Performance

Noise principally affects human performance in tasks requiring communication and at extremely high noise levels above 140 db, body functions may be disturbed. The effects on speech projection and reception were previously discussed in Section 3 above.

Interference with Comfort and the Instigation of Annoyance

The noise criterion based upon the damage risk criterion may still be too high for adequate pilot comfort. A "comfort criterion as such

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has not yet been developed; however, much experience has been gained by the noise tolerated by civilian airline passengers. Sound pressure level spectra for the interior of present day civilian propeller driven aircraft are shown in Figure 8. Also shown are the NCA 70 and 75 criteria which closely approximate the airline spectra. These curves probably closely represent a "comfort" criterion which could be applied to military aircraft. (References 6, 7, 8 and 9)

Attenuation Requirements

Of the spectra shown in Figures 1 and 2 only the cruise condition for high performance manned aircraft need be considered. All the other noise spectra will either be of lower magnitude or will last for only short duration; i.e. takeoff, re-entry, etc. Of course, during certain short duration noise, such as an emergency condition, it must be assumed that communication is possible with a higher vocal effort. (The cruise condition for the space vehicle will be controlled by internal noise sources and is not considered here.) The cruise noise is re-plotted in Figure 8.

The difference between the cruise noise spectrum and the criteria listed above will give the attenuation required. This is shown in Figure 9.

In order to achieve the 85 or 95 db damage risk criterion, only a minimum protecting device is required. Most helmets and other ear protection already are capable of such attenuation. However, to achieve the "comfort" criterion, additional attenuation will be required in the 300 - 600, 600 - 1200 and 1200 - 2400 CPS octave bands. Large low frequency attenuation is apparently not necessary.

4.2   Microphone Development

4.2.1   Tooth Microphone

During the exploratory phase it was discovered and proved that a tiny accelerometer fastened to an upper front tooth will detect highly intelligible speech and discriminate strongly against external noise. The noise rejection is equal to the AIC-10 gradient microphones with the virtue that the tooth microphone is fixed in position, so that speech pickup is not subject to misadjustment.

The mounting of the microphone to the tooth has been refined to a so-called "tooth veneer." (See Figure 10) The tooth veneer is a custom fitted device but possesses advantages such as ease of retention, comfort and space for the eventual placing of a tiny device to transmit the speech signal out from the man, thereby eliminating the lead between the accelerator and amplifier.

A comfort study using three subjects has proved that the tooth veneer and accelerometer can be worn continuously for a period of 40 hours. The three subjects who took part in this study were able to eat, drink, and sleep normally during the test. No discomfort of any type

was experienced.

An amplifier was developed to match the tooth microphone to the AIC-10 system. It features a high input impedance, low output impedance and operates on 28 v DC supply.

Further details on the tooth microphone may be found in Appendix 3.1.

4.2.2 Forehead Microphone

During the exploratory program it was discovered that highly intelligible speech may be detected with a vibration sensitive transducer mounted on the forehead. Its greatest virtue is that it frees the mouth area completely and its position is fixed (see Figure 11).

Development partially sponsored by North American Aviation, Inc., occurred during Phase II. Measurements were made to determine the effect of the following parameters on the operation of the forehead microphone in noise: (1) microphone type - diaphragm vs inertial; (2) contact pressure; (3) forehead position; (4) material between microphone and forehead.

The results of these measurements are that (1) an inertial type transducer affords 10 db greater signal-to-noise ratio (S/N) over a diaphragm contact or air cavity transducer;(2) increasing the contact static pressure over 0.3 psi does not improve the S/N. A minimum of 0.2 psi is required; (3) the microphone can be mounted within an imaginary rectangle 1 inch high and 3 inches wide, centered on the forehead without appreciable change in performance; (4) a thin headband between the transducer and the forehead will not decrease the S/N.

Progress was made in adapting two existing commercial units, the Sonotone O-1 and the military MC-253B,to the AIC-10 system. A small transistor amplifier equalizer was constructed.

Future work to be performed for North American Aviation, Inc., is intended to include: (1) basic transducer design in order to obtain the maximum S/N; (2) miniaturization with a design goal of 1/2 inch diameter, 1/4 inch thick; (3) adaptation to the AIC-10 system with a goal of eliminating any electronic adaptor altogether; (4) comfort studies; (5) system articulation tests.

Further details on the forehead microphone may be found in Appendix 3.2.

4-3 Reception System Development

4.3.1 Bone Conduction Reception

A bone conduction receiver placed on the forehead would eliminate the usual receiver from the ear region altogether. One most attractive prospect is that the same transducer gives effective speech pickup and hence, the prospect that a single transducer may replace the present three. Of course, no side tone would be possible.

A theoretical analysis of a bone conduction receiver on the forehead was made using an electromechanical analog. However, an attempt to

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verify the analog by measuring the bone conduction threshold proved fruitless.

Measurements were made to determine the ratio of the bone conduction threshold on the forehead with the ears occluded, and the air conduction threshold at the ear. For driving areas approximately 1 inch in diameter the difference is approximately 80 db at low frequencies, and 65 db at high frequencies. These results may be used to determine the sound pressure level required on the forehead to achieve any signal-to-noise ratio. For example, to achieve a 0 db S/N ratio in 120 db jet noise, sound pressure levels on the order of from 150 to 190 db, dependent on frequency, on the forehead would be necessary. The question arises as to whether (1) such levels can be generated and (2) whether pressures of this magnitude will be damaging. The possibility of cavitation occurring in the blood vessels must be considered. Cavitation will occur within a liquid if a peak negative pressure exceeds the static pressure of the liquid. The static pressure in the capillaries corresponds to 18 to 30 mm hg, which is equivalent to a sound pressure level of 163 – 166 db. Hence, sound pressure levels generated on the forehead should not be allowed to exceed 163 – 166 db or else cavitation may occur. If the cavitation phenomenon can occur, then it imposes a serious limit on the usefulness of a bone conduction receiver for the intended purpose. The cavitation phenomenon is described in more detail in Appendix 4.1.

The work was set aside because of the question of cavitation. Unless a more efficient transfer of energy can be achieved between the forehead receiver and the hearing mechanism, the bone conduction receiver appears impractical. For further details see Appendix 4.1.

4.3.2 Horn-Coupled Receivers

It was demonstrated in the exploratory program that a small dynamic receiver could be coupled to the ear by means of an acoustic horn and deliver adequate speech level at the ears, even though the periphery of the horn is spaced slightly from the head surface.

This system offers many advantages over the conventional mounting at the ear; among them, improved comfort and decrease in helmet size.

A prototype Fiberglas horn was formed which was built into a production helmet, the Bill Jack Sound Absorb. This helmet choice was dictated by availability and by the fact that it is a narrow helmet and shows the horn to better advantage. (See Figure 12)

Physical measurements indicate that the horn integrated into a standard helmet can provide sufficient level for use in high noise fields when driven by an earphone unit.

Other advantages found in incorporating the horn into the helmet are: (1) the horn utilizes unused helmet space; (2) the center of gravity of the helmet is lowered; (3) it strengthens the helmet shell. The horn concept is highly versatile. It may be used in helmets with a foam liner or ones with webbing. Where improved attenuation is necessary, cushions could be applied to the periphery of the horn. Further description of the horn may be found in Appendix 4.2.

4.3.3 Loudspeaker Mounted Inside an Experimental Plastic Helmet

It was shown in the exploratory program that a small loudspeaker unit can be mounted in unused space within a helmet and provide sufficient sound level for good performance. The helmet is spaced away from the head without contact, and there is no further acoustic coupling. (See Figure 13).

In a series of measurements, the spherical plastic helmet developed during the exploratory program was used. The purpose of these measurements was to elaborate on the simple tests which were previously conducted in order that information as to optimum location of transducers and absorption could be determined.

There were two allied operational factors to be considered in the acoustical design of a speech reception system in a helmet of this type. These are crash protection and vision requirements. Since the head must move freely within the helmet, the locations of crash protection (which can also serve as acoustical absorption) and transducers are limited if peripheral vision is not to be impaired.

The response of a small loudspeaker radiating into a spherical helmet worn by a dummy head was found to be extremely complex due to the normal modes of vibration determined by the boundary conditions. Although the response of the loudspeakers was found to be reasonably flat when measured on the axis in a free field, variations on the order of ± 10 db were observed in the helmet. It was necessary to examine the frequency response as measured both at the ears and at the mouth. The response at the lips will in part determine the gain limitation (which limits sidetone level) within the helmet due to acoustic feedback.

Based upon comparative smoothness of response, a speaker mounting location opposite each ear or on top of the helmet is the best.

This approach was not further pursued for several reasons: (1) prediction of the noise in future aircraft (Section 3.1) indicates that large low frequency attenuation as afforded by the spherical helmet will not be necessary; (2) the size of the spherical helmet appears impractical for future aircraft where space requirements are paramount; (3) other coupling means such as the horn coupled receivers previously described or the semi-insert plugs with miniature receivers discussed in the next section offer substantial advantages in smoother response.

Further information on the loudspeaker mounted within a helmet may be found in Appendix 4.3.

4.3.4 Miniature Receivers in Semi-insert Ear Protectors

Under Contract AF33(616)-3048 Western Electro-Acoustic Laboratory has developed a semi-insert aural protective device. (See Figure 14). Preliminary studies indicate that one size will fit approximately 85% of the adult male population. The comfort prospect is good.

The earplug-receiver combination offers approximately 23 db attenuation below 1000 CPS and 27 db attenuation below 1000 CPS.

A small hearing-aid type receiver may be fitted into the plug with a special adaptor.

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The frequency response is reasonably uniform when measured in a 2 cc coupler. The sensitivity at 1000 CPS is 112 for 1 milliwatt input. Hence, sufficiently high sound levels may be established at the ear for any contemplated noise field.

Further information about the semi-insert receiver may be found in Appendix 4.4.

4.3.5 Electrostatic Loudspeaker

A major prospect predicted by the exploratory program and not studied further in Phase II is the electrostatic type receiver. This type offers excellent performance as a thin unit lining the helmet in the ear area. One problem, which tends to be exaggerated, is due to the polarizing voltage and high driving voltage. We have found an interesting possibility of push-pull electrostatic drive which does not require polarization. The system is subject to analytic study and simple experimental verification. In terms of size and weight potential there is no better prospect.

4.4 Miscellaneous Studies

4.4.1 Acoustic Feedback

Acoustic feedback has been studied theoretically and the parameters affecting feedback isolated. A technique for determining the signal-to-noise ratio at the ear as a function of frequency has been derived. These parameters can be measured separately in order to analyze the possibility of improvement where acoustic feedback is limiting the performance of a communication system. For further information see Appendix 5.0.

4.4.2 Correlation of the Intelligibility of CVC and PB Words in Noise

In the exploratory program a special list of CVC words (consonant-vowel-consonant) words was assembled for use in the articulation testing. These words possess several advantages, particularly that they require little training period and provide a sensitive and efficient evaluation of a system's performance. In most intelligibility testing, PB words have been used. Hence, in order to correlate our results with those found in the literature, a comparison of the intelligibility of CVC and PB words was made. The results of this study are shown in Figure 15. For further information see Appendix 6.1.

4.4.3 Sentences Based Upon Air Force Vocabulary for Use in Intelligibility Testing

Special test material based upon typical Air Force communications was assembled for use in prototype system evaluation in noise. The sentences were formed in such a way as to stress recognition of a limited vocabulary

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and to minimize rote and contextual memorization. For further
information see Appendix 6.2.

4.4.4 Relation Between Peak, Long-time Average, and VU Meter
Peak Levels for Speech

Much confusion in the literature results when referring to
signal-to-noise ratio. The reason for this confusion is the manner in
which the speech signal is measured. The relation between the various
techniques for measuring speech levels has been evaluated. Taking
0 db as a reference level, the averaged results are:

Long-time Average	0 db
VU Meter Peak	+8 db
Peak	+18 db

That is to say VU meter peak is 8 db higher than the long-time average
over a sentence, but 10 db less than the actual speech peaks. For
further information see Appendix 6.3.

4.4.5 The Limits of Ear Protection

Until recently it had been our experience that if a listener
receiving communication through headphones in a high noise field used
earplugs under the receivers, the intelligibility of reception would be
improved. Recently qualitative reports indicated a converse reaction
when certain advanced muff protectors were used as ear cushions. Tests
indicate that the attenuation of a combination of earplug plus muff may
be 10 db poorer than the muff alone.

This finding has implications both in regard to voice communica-
tion reception and in regard to the behavior of ear protectors as such.

In regard to communications, we are now alerted that we are
approaching the maximum available ear protection, and that the muff
type detector has now been developed to the point where its attenuation
not only exceeds that furnished by the best available earplug, but also
that greater attenuation can no longer be achieved by the combination
of protective devices.

Experimental tests performed at Western Electro-Acoustic
Laboratory strengthen the theory that the attenuation of aural protective
devices is limited by the vibration of the skull in the sound field; that
the limit will be most evident in the frequency region of the first flexural
mode of skull vibration, which varies from 800 to 2000 CPS; that the
limiting mechanism is the vibration of the skull with respect to a
relatively immobile protector; that therefore the attenuation limit will
be increased by making the protector as light in weight and large in
volume as possible, and by coupling it to the head over a large contact
area and as rigidly as possible.

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4.5 System Articulation Testing

Articulation testing in a noise field was performed on useful combinations of speech projection and reception systems. In all cases the components of the system were adapted to and used with the AIC/10 amplifying equipment so that the results are realistic in terms of aircraft use. In the cases of the forehead microphone and the tooth microphone, special miniature battery operated, transistorized amplifiers with built-in equalizers, were developed for this purpose. Details of these amplifiers are in Appendixes 3.1 and 3.2.

The following systems were evaluated with both the talker and listener in a noise field:

System	Figure	Microphone	Receiver	Ear Protection
1	16	Tooth	Dynalab D-58	W. E. A. L. Semi-insert
2	17	M-33/AIC	ANB-H-1A Horn-coupled	Bill Jack Sound Absorb.
3	18	Forehead	Dynalab D-58	W. E. A. L. Semi-insert
4	19	Tooth	External Loudspeaker University MM-2	Bill Jack Sound Absorb

These combinations were based upon potential application and considerations such as propensity for acoustic feedback.

Articulation testing was performed using special test material representative of Air Force communication. Both the talker and the listener were in a jet noise spectrum, shown in Figure 20. The results of the testing are as follows:

System	Overall Jet Noise Level in db	% Articulation
1	120	96
2	120	94
3	110	96
4	120	66
4	110	89

Two talkers and two listeners were used. Each score represents a total of 20 sentence lists of 20 sentences each.

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5.0 SUMMARY OF RECOMMENDATIONS FOR FUTURE
RESEARCH AND DEVELOPMENT

A continuing program and a priority list, subject to enlightened modification, will be outlined. The following problems, prospects, or developments require continued investigation.

5.1 Noise

The noise field surrounding a man's head in an aircraft is a major factor in determining his ability to communicate, and to a large extent dictates the choice of transducers for speech projection and reception and also the headgear which he must wear for noise exclusion. Phase II of our program has applied all available data and theoretical approaches to predict the limits of noise which may be expected in future aircraft and spacecraft as a function of operating conditions. Three factors control the conditions:

The available power or thrust determine: the potential speed in horizontal flight; the acceleration and therefore potential speed vs altitude in vertical ascent. The noise developed by propulsion is determined by thrust or power scale.

The speed at any altitude is limited by heating and therefore by heat tolerance provisions. Aerodynamic noise, which is developed exterior to the craft, increases rapidly with speed and becomes a controlling factor in determining interior noise as the propulsion noise is left behind.

Structural design determines the reduction in noise from outside to inside the craft. New structural techniques tend to decrease weight and hence noise exclusion.

The predictions of Phase II are based upon the best available information on existing or expected trends in the above three factors. It is important to realize that considerable extrapolation is used from data describing existing flight domains. Furthermore, the crucial nature of the noise field is not sufficiently recognized and opportunities for collection of noise data are not exploited.

Our best predictions now indicate that if acoustic competence is applied to structural and interior design the noise levels should not exceed values which presently available and proposed improved communication equipment can tolerate. However, it is essential that we conscientiously monitor the trends of the three controlling factors. A major breakthrough in any of these three factors beyond that anticipated in our predictions could greatly alter the noise environment. We know very little about noise-producing atmosphere in outer space. We must use every possible opportunity to collect noise data from advanced aircraft and missiles. Particular attention should be given to emergency conditions to assure that resulting excessive noise does not cause failure of communications and hence contribute to the emergency. In our own consulting program, increasing opportunities are arising for monitoring and encouraging noise measurement. The important thing is that data be cor-

related for specific application to the communication program as it becomes available.

5.2 Speech Projection

Phases I and II have clearly shown potential solutions to the wearability problems from two new speech projection methods, the forehead contact microphone and the tooth accelerometer.

The forehead contact microphone is simple to apply and straightforward for development. Its performance in noise is not competitive with a good noise cancelling microphone properly used. However, its performance is not so likely to deteriorate because of mispositioning. Also, the deterioration of the acoustic path with increasing altitude, which is inherent in a microphone, does not occur for a contact device. The signal-to-noise ratio of the head contact microphone without helmet attenuation is adequate for 110 db overall jet noise, 95 db S.I.L. with raised voice level. Additional exploratory work is required only to demonstrate the utility of this device in a small inertial framework and to prove its performance capabilities within the system framework.

The tooth accelerometer has all the operational advantages of the forehead contact microphone, has been proved to be highly acceptable from a wearability standpoint for more than 40 hour use, and has the additional advantage of 15 db better S/N ratio, being equal in performance to the best noise-cancelling type in optimal use. It is much farther from applicability; the present transducer is a high impedance type. The electrical lead is a more imagined than actual detraction from utility, but every effort should be made to eliminate it. We believe that inductive coupling with no lead whatever is technically feasible. In fact, we foresee the possibility of eliminating cable connection to the airplane altogether so as to allow freedom of motion within the crew quarters.

Both of these new voice transmitters seem to offer excellent solutions to the wearability problems which initiated the program. Both prospects should be encouraged as rapidly as possible.

5.3 Speech Reception

Phase II of the program has clearly demonstrated the acoustical feasibility of coupling a small receiver unit to the ears using acoustical horns. The result is a great decrease in helmet width and potentially in weight. The ear comfort aspect is solved because no contact of the horns with the ears or head is necessary. A question which is under study is whether the attenuation of the helmet without ear seal will be adequate for expected noise fields. Another detail to be investigated is the adaptation of existing driver unit types for optimal performance with the horn coupling.

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A major prospect predicted by Phase I and not studied further in Phase II is the electrostatic type receiver. This type offers excellent performance as a thin unit lining the helmet in the ear area. The problem which tends to be exaggerated is due to the polarizing voltage and high driving voltage. We have found an interesting possibility of push-pull electrostatic drive which does not require polarization. The system is subject to analytical study and simple experimental verification. In terms of weight and size there is no better prospect.

The use of loudspeakers for reception has heretofore been considered only as an auxiliary measure. Phrase I showed that in terms of available acoustic output, the loudspeaker is capable of greater utility. A deterent is the loss of effectiveness in the event of sudden and complete decompression at very high altitude. Nevertheless, the prospect of extreme mission duration, during which the noise level may be quite low and the continuous tolerance of a helmet unthinkable, commends serious reconsideration of loudspeaker reception, with the helmet system as an emergency standby facility.

5.4 Basic Studies

During Phase I the technique of quantitative speech articulation measurement was greatly advanced. Phase II has related this method quantitatively to older methods and developed a simplified scheme for overall system evaluation using standardized communication phraseology.

There are several basic problems which require further investigation in connection with evaluation of communication components by physical methods and by articulation testing, with the hope of improving correlation between these methods. It is granted that the ultimate method for evaluation is by means of articulation testing. However, one of the major objectives of a continuing exploratory program should be the discovery of the significant physical factors of speech projection which will correlate sufficiently with intelligibility so that the simpler physical tests will suffice. Already we feel reasonably comfortable with calculation methods for receiving systems using the Articulation Index concept. Such a method does not exist for a speech projection system if the pickup position or electrical speech treatment is likely to produce atypical speech. We have demonstrated that in articulation testing the consonant sounds should be stressed. In the early phase of the initial program, we had hoped that physical parameters of the consonant sounds could be measured and that the consonant-to-noise ratio would be the essential factor to correlate with articulation. However, it becomes clear that there is much to be learned about the physical nature of consonants before even the time period of a consonant can be defined. We still believe that this basic concept is correct and that some reasonable percentage of exploratory effort should be devoted toward these problems. The following would be the order of approach:

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During the initial program the signal-to-noise measurements which are reported have been based upon the "static" noise. It is known that, particularly with the better microphones, the noise level is altered by the process of articulation. It will be worthwhile to evaluate the difference between the static and dynamic noise.

The prospect of physical measurement of consonant-to-noise ratio is dependent upon a better technique for short interval speech spectrum analysis. An example of the method is the use of a rotating playback head for basic speech studies at the Bell Laboratories. This technique will permit the measurement of consonant-to-noise ratio, which can then be correlated with speech articulation measurement.

There is apparently no existing data on the relative interference of noise with the three basic cues which contribute to consonant intelligibility. The measurement of consonant level in actuality requires measurement of a variety of cues which, when properly oriented as to relative level, will permit discovery of the durability of these cues in noise or, conversely, of the consonant cues which are important to speech intelligibility at low values of signal-to-noise ratio. This basic study will contribute greatly to the understanding of the emphasis which should be given to frequency range and clipping techniques in the preservation of maximum intelligibility in a given noise. Lacking such basic understanding, a cut and try approach to the achievement of maximum intelligibility will undoubtedly be much more costly.

The speech intelligibility testing which has been done during the initial microphone investigations has been recorded in such a manner that a "confusion" matrix can be assembled for the performance of any one system. This procedure was highly recommended by the speech experts who cooperated with the program. We understand that if such a confusion matrix is assembled, it is possible to use it for diagnostic purposes which would permit definition of the shortcomings of a given system in regard to specific speech sounds which would then be extremely useful for guiding the improvement of that system. It would be of great interest to attempt this method of comparing the performance of two systems and then, if it is found helpful, to use that guidance for the improvement of the tooth accelerometer pickup.

6.0 SPECIFIC RECOMMENDATIONS FOR PHASE III OF THE PROGRAM

1. Continue the monitoring and correlation of all available data on noise in aircraft with the objective of defining the noise environment within which communication must be possible as a function of operational condition, and to improve the long range prediction of future noise exposure.

2. Continue the investigation of the forehead contact microphone to define the limits of its utility in noise and its size prospect in an inertial configuration.

3. Continue the investigation of the tooth accelerometer microphone with the objective of eliminating the electrical lead connection to exterior equipment and if possible, the connection of the entire helmet system to the aircraft.

4. Study the effects of altitude on the performance of both contact projectors in comparison with the acoustic coupled microphone.

5. Define the optimum matching of receiver unit and horn coupling within a helmet without ear contact.

6. Analyze the operational capability of an electrostatic receiver using a push-pull unbiased drive.

7. Define the operational limits of loudspeaker speech projection for use under normal, non-emergency conditions in very long duration missions.

8. Continue basic studies of speech in noise to: determine the significance of modulation of external noise by the speech process; determine the relative durability of consonant articulation cues in the presence of noise; further the objective of rapid evaluation of articulation capability in terms of significant physical speech and noise parameters.

9. Verify all performance measurement within complete experimental interphone system context using as a measure the articulation efficiency of standardized Air Force command phrases as a function of ambient noise level, speaker effort, and simulation of other pertinent operational stress.

10. Present all results of exploratory investigation, insofar as possible, in terms of quantitative specifications for prototype hardware development.

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7.0 SPECIFICATIONS FOR CONTINUING DEVELOPMENTS

7.1 Forehead Microphone

General

It is highly desirable to develop a forehead contact transducer which will be directly interchangable with the AIC microphones without the use of additional amplification. At the same time, the transducer should be as small and light as possible for optimum wearability.

These two goals are apparently in conflict. Research is first necessary to determine the maximum sensitivity which can be achieved in a specialized small transducer. If additional amplification or impedance matching is required for complete interchangability with the AIC microphones, then it must be achieved in an auxiliary amplifier. Therefore, development should proceed in two phases:

1. Transducer design: high acceleration sensitivity, small size and low weight.
2. Amplifier design as needed to adapt optimized transducer to AIC interphone equipment.

Specific

Physical Characteristics of the Microphone:
1. Diameter -   0.500 in. - 1.00 in.
2. Thickness -   0.250 in. maximum
3. Weight 10 - 20 grams

Physical Characteristics of Retention System:
The contact pressure of 0.3 psi minimum, 0.5 psi maximum, should be provided by a suitable retention system. The retention system should be adaptable to any protective helmet under which the microphone may be used. The retention system should provide vibration isolation between the transducer and any large areas such as the helmet shell.

Electrical Characteristics of the Microphone - Amplifier:
The forehead microphone and any electrical amplification required must produce an output voltage equal to or greater than and at the same impedance as the AIC-10 microphones at the same speaking efforts.

The following information is fundamental to the design.

1. Acceleration spectrum on the forehead at a raised speaking effort:

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		Octave Bands			
75	150	300	600	1200	2400
150	300	600	1200	2400	4800
-49	-44	-40	-38	-40	-42 (db re 1 g)

2. Output voltage from AIC-10 microphone (M-33) at a raised speaking effort:

-109	-99	-83	-81	-76	-88 (db re 1 volt)

3. Input impedance of AIC interphone equipment, microphone input - 5 ohms.

4. Signal-to-noise ratio in amplifier - at least +10 db between -300 - 4800 CPS with a normal conversational speaking level input to microphone.

5. The microphone and amplifier as required shall not be sensitive to external magnetic or electrostatic fields, moisture, or temperature variation.

6. The response of the microphone shall not change appreciably with altitude

Response vs altitude shall be measured with the forehead microphone mounted on a human subject speaking at a constant effort.

Intelligibility Specification:

The microphone system shall be capable of achieving at least 90% sentence intelligibility in an overall jet noise of 110 db with a speech interference level of 95 db.

Wearability Specification:

The microphone must be sufficiently comfortable to be worn continuously for 40 hours.

7.2 Tooth Microphone

General

Development of the tooth microphone should be divided into two phases:

Phase 1. Completely integrate an existing or readily developed accelerometer into the ooth veneer. This should include encapsulation, ruggedization and adaptation to the AIC-10 interphone amplifiers. The electrical lead between

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the accelerometer and amplifier is retained. The development which has proceeded thus far under the contract includes these items with the exception of encapsulation of the accelerometer for moisture proofing, and ruggedization of cable attachment. These should be readily accomplished.

Phase 2. The purpose of this phase would be to eliminate the lead between the accelerometer and the amplifier. This lead which protrudes from the lips is believed to present the main psychological block against the tooth microphone.

It is believed that the output of the tooth accelerometer can be coupled or transmitted to an external receiver without the necessity of an electrical lead. The external receiver may be located on the operator's helmet, or some other remote location. The output of this receiver would then be fed to the AIC-10 interphone equipment. Investigation would be necessary to determine the most feasible manner to transmit the signal from the tooth. One technique would be to couple the varying capacity of the accelerometer to the tank circuit of an external oscillator. Another might be to imbed a tiny radio transmitter within the tooth veneer.

7.2.1 Specifications – Phase I

(a) Physical Characteristics of the Accelerometer
    1. Diameter   0.25 in. maximum
    2. Thickness (including lead) - -.375 in. maximum
    3. Weight   (1 - 2 grams
(b) Physical Characteristics of Tooth Veneer
    1. Size, weight vary. The tooth veneer in its present form is custom fitted to the individual.
    2. Material - the material shall be non-toxic and durable.
    3. Means shall be provided in the veneer for the attachment of the tooth accelerometer. The attachment point shall be over the incisors.
(c) Electrical Characteristics of Tooth Microphone Amplifier System
    The forehead microphone and any electrical amplification required must produce an output voltage equal to or greater than and at the same impedance as the AIC-10 microphones at the same speaking effort.

The following information is fundamental to the design:

1. Acceleration spectrum on the tooth veneer at a raised speaking effort:

	75	150	300	600	1200	2400
Octave Bands, CPS	150	300	600	1200	2400	4800
	-24	-22	-22	-21	-40	-42 (db re 1 g)

2. Output voltage from AIC-10 microphone (M-33) at a raised speaking effort:

Octave Bands, CPS					
75	150	300	600	1200	2400
150	300	600	1200	2400	4800
-109	-99	-83	-81	-76	-88 (db re 1 volt)

3. Input impedance of AIC-10 interphones, microphone input - 5 ohms.

4. Signal-to-noise ratio in amplifier, at least +10 db between 300 - 4800 CPS with a normal conversational speaking level input to microphone.

5. The microphone and amplifier as required shall not be sensitive to external magnetic or electrostatic fields, moisture, or temperature variation.

6. The response of the microphone shall not change appreciably with altitude.

(d) Intelligibility Specifications
The microphone system shall be capable of achieving at least 90% sentence intelligibility in an overall jet noise of 120 db with a speech interference level of 95 db.

(e) Wearability Specification
The microphone must be sufficiently comfortable to be worn continuously for 40 hours.

7.2.2 Specifications - Phase II

(a) Physical Characteristics of the Microphone
The microphone shall be sufficiently small to be encapsulated within the tooth veneer.
(b) Physical Characteristics of Tooth Veneer
Same as previously noted in Phase I.
(c) Electrical Characteristics of Tooth Microphone Amplifier System
1. Items 1 - 6 same as in Phase I.
2. A device shall be incorporated within the tooth veneer to transmit the output of the accelerometer to an external receiver. The transmitter may be in the form of a loop for inductive or capacitative coupling, or a miniature radio frequency transmitter.
3. A device shall be constructed to receive the signal transmitted from the tooth veneer. It will also contain necessary amplification and impedance matching to adapt to the AIC interphone equipment.
4. Stray magnetic or electrostatic fields shall not affect the operation of items 2 and 3 above nor shall the operation of items 2 and 3 produce fields which will affect other equipment.
(d) Intelligibility Specification
Same as Phase I.

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(e) Wearability Specification
Same as Phase I.

7.3 Horn-Coupled Receivers

General

In order to fully realize the advantages inherent in the horn-coupled receiver concept, it is necessary to specify an integrated helmet-receiver combination.

However, with slight modification, the horns could also be installed in presently available helmets without the helmet width reduction potentially available.

7.3.1 Horn Specifications
1. Physical Characteristics
The horns shall be fabricated out of suitable material such as Fiberglas or hard neoprene.

A range of adjustment shall be provided within the helmet for ear-to-ear spacing and ear position by flexible joints and adjustable mounting.

The horn opening and mounting shall be designed so that it will fit 90% of the adult male population.

2. Acoustical Specifications
The horn shall be exponential in audio area vs axial distance.
It shall have a cutoff frequency below 400 CPS.

The horn when used with an appropriate driver shall deliver 90 db SPL at the ear for 1 mw input over a frequency range of 300 - 5000 CPS with no part of the horn mouth touching the ear.

3. Comfort
The horn when used with appropriate helmet must be reasonably comfortable over 40 hours of continuous wearing.

7.3.2 Horn Driver Specifications

1. Physical
(a) Diameter   1.00 in.
(b) Thickness   .40 in.
(c) Weight   15 - 20 grams
2. Electrical and Acoustical
(a) The driver shall deliver 90 db at the horn mouth for 1 mw input
(b) The driver must be capable of utilizing 1 watt electrical input
continuously.

7.3.3 Helmet Specifications

1. **Physical**

   Minimum external dimensions are desired within the usual Air Force requirements of population fit, strength and protection.

   Weight of the combination of helmet, receiver, and coupling horns shall not exceed 4 pounds.

   No portion of the coupling horns or helmet should touch the ears. The helmet seal around its face and neck opening should be a minimum consistent with acoustical requirements.
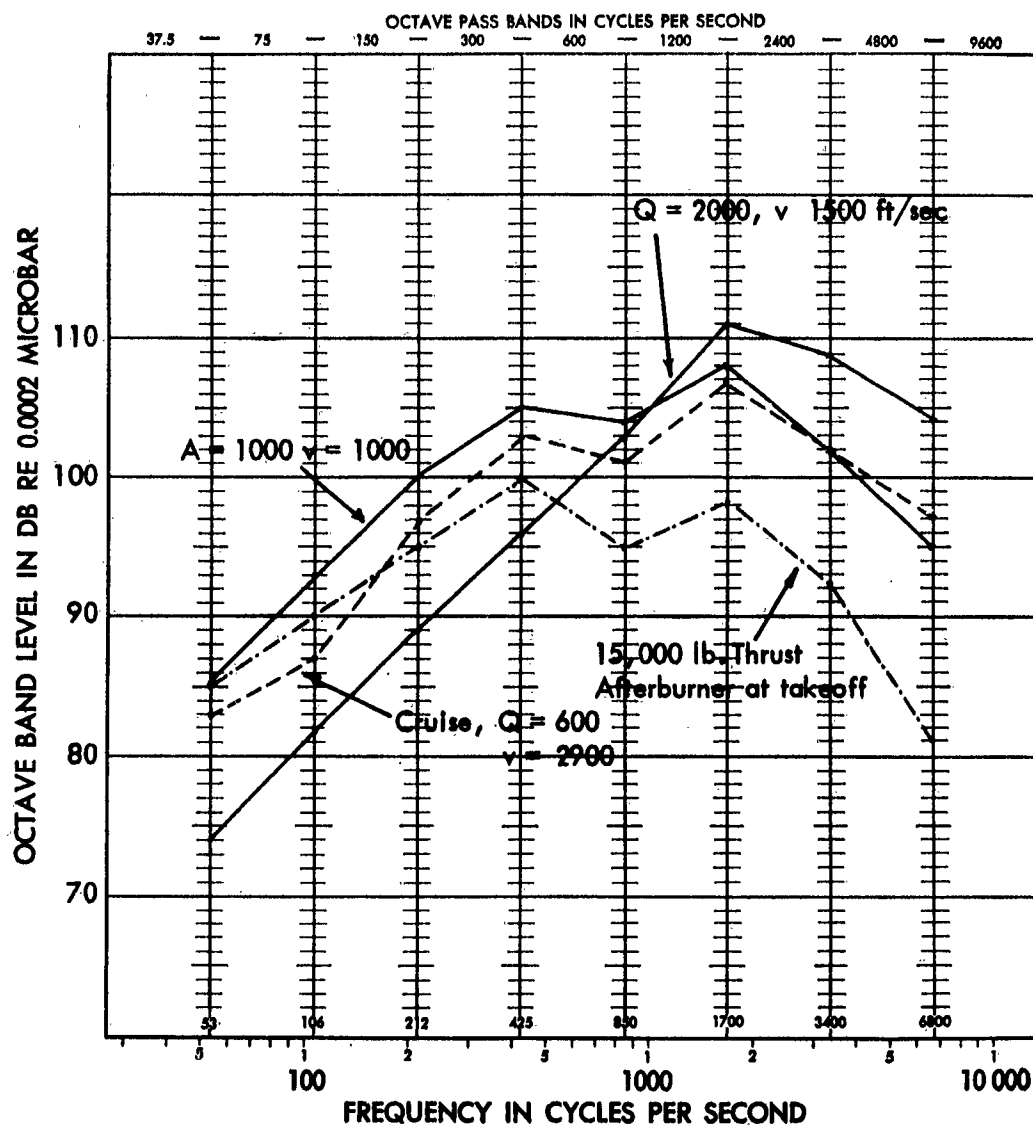
2. **Acoustical Specifications**

   Minimum attenuation with the horns and helmet in place shall be:

Frequency CPS:	125	250	500	1000	2000	3000	4000	6000
Attenuation:	3	12	20	26	30	30	30	30

In order that the 75 db NCA noise criterion is not exceeded under cruise conditions for a high performance manned aircraft.

References

1. Contract AF33(616)-3710 Western Electro-Acoustic Laboratory Progress Report dated 29 January 1959.

2. Contract AF33(616)-3710 Western Electro-Acoustic Laboratory Final Report, Phase I, dated February 1958.

3. Pickett and Kryter, AF RC - TR - 55 - 4.

4. Handbook of Instructions for Aircraft Designers, ARDC Manual 80-1, Revised April 1957.

5. Harris, "Handbook of Noise Control," Chapter 34, McGraw-Hill Book Co., Inc., New York, 1957.

6. MIL A8806 (ASG) 25 October 1956.

7. Rosenblith, W. A., Stevens, K. N., and the Staff of Bolt Beranek and Newman, "Noise and Man," Handbook of Acoustic Noise Control, Vol. 2, WADC June 1953.

8. Beranek, L., "Criteria for Office Quieting Based on Questionaire Rating Studies," Journal of the Acoustical Society of America, Vol. 28, No. 5, Sept. 1956, pp 833 - 852.

9. Unpublished data in Western Electro-Acoustic Laboratory files.

INTERNAL SOUND PRESSURE LEVEL

INSIDE MANNED AIRCRAFT FOR STATED CONDITIONS

Figure 1

OCTAVE PASS BANDS IN CYCLES PER SECOND

1.2 million lb. Thrust at Launch
Rocket Capsule 100 ft. Forward

Re-entry
Q = 3000
v = 1700 ft.
per sec.

A is a heavy single-walled structure
B is a light double-walled structure
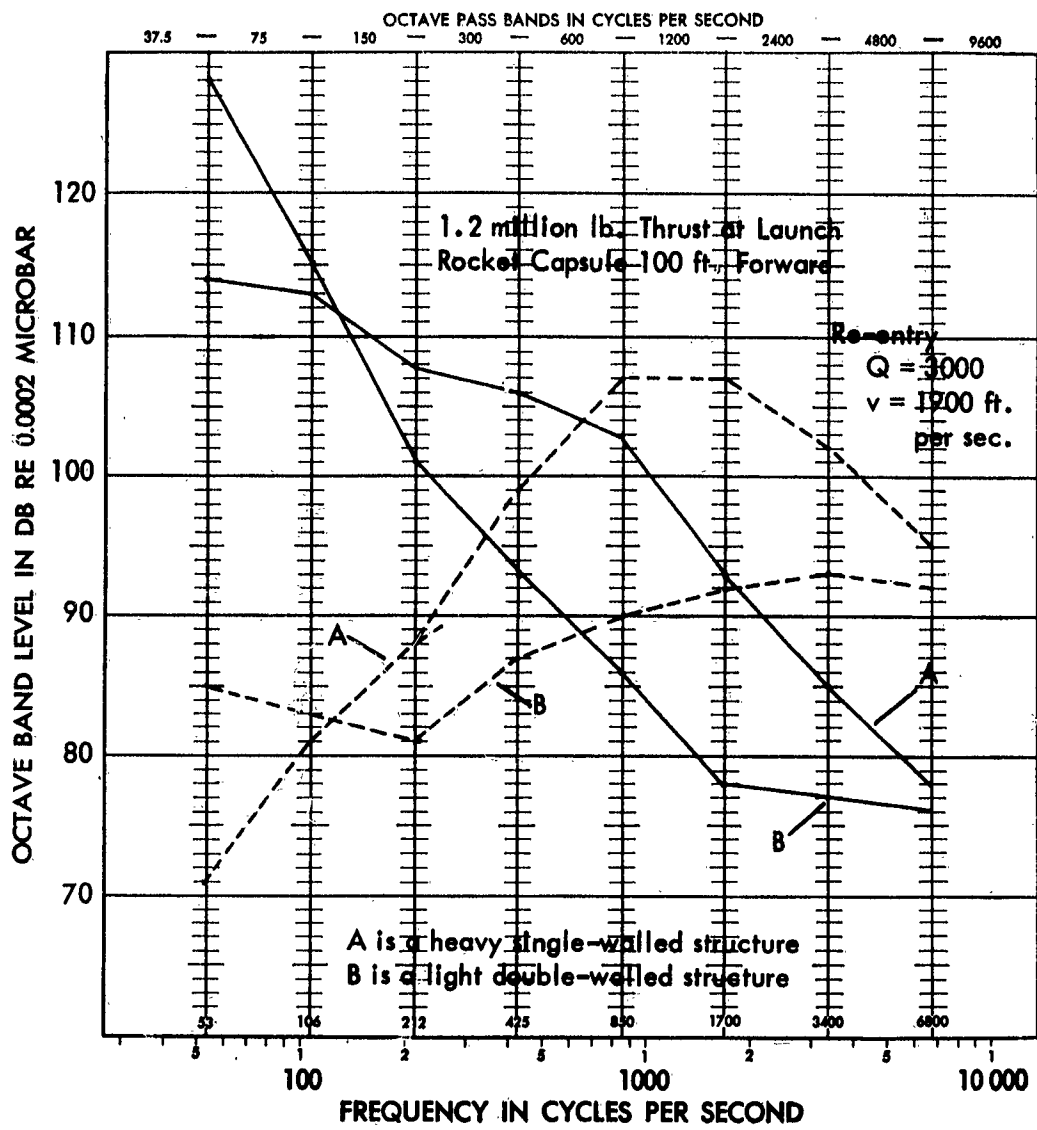
MAXIMUM INTERNAL SOUND PRESSURE

LEVEL INSIDE SPACE VEHICLE CAPSULE

Figure 2

OCTAVE PASS BANDS IN CYCLES PER SECOND
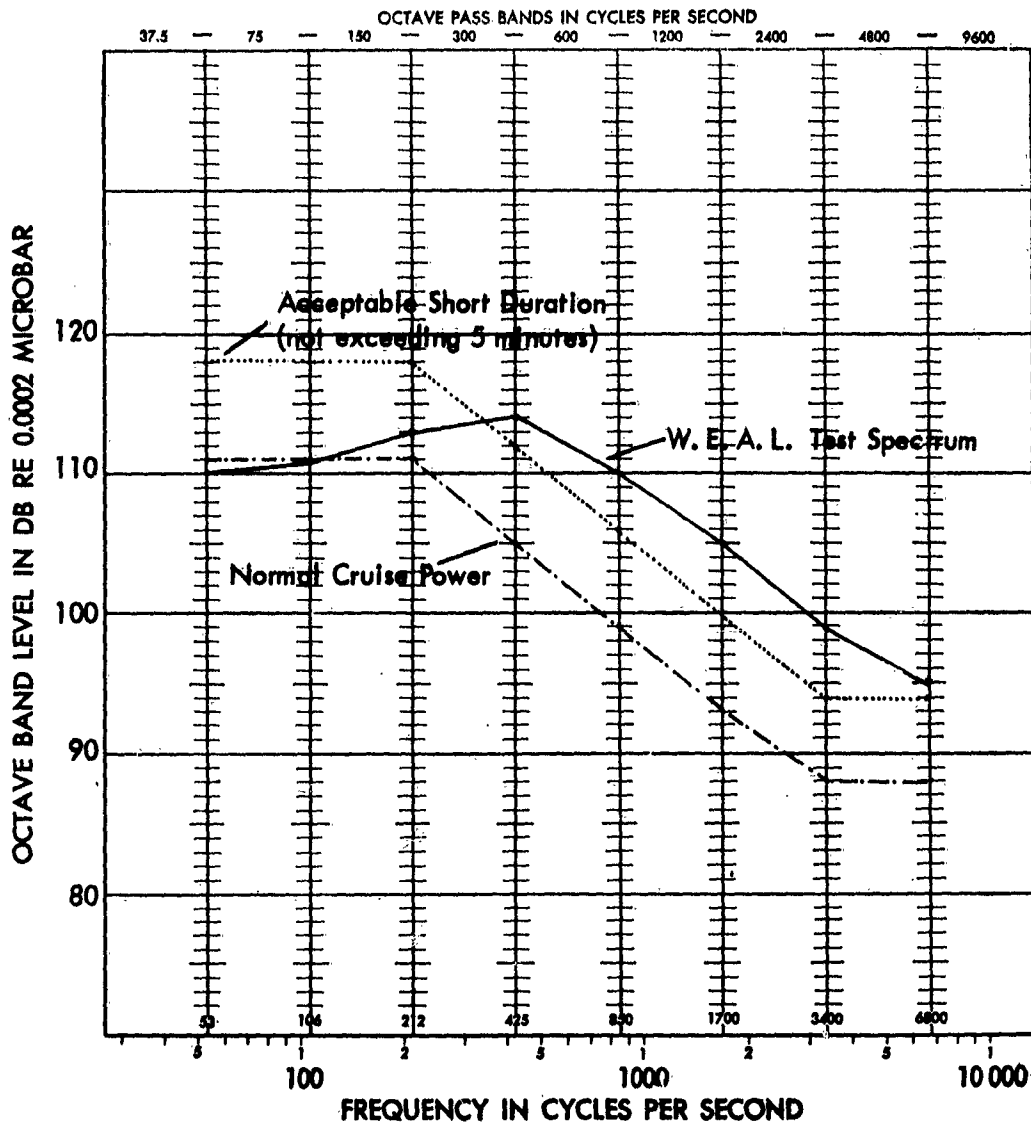
W. E. A. L. TEST JET SPECTRUM

Notes: The jet test was derived from data on noise in jet
aircraft cockpits found in WADC TN 56-411. It
was used in the articulation tests performed on the
microphones and receivers in Figures 4 and 5.

Figure 3

MICROPHONE TYPE	NOISE EXCLUDER
1. M-34 Gradient	Noise Shield
2. Tooth	Helmet
3. Probe Pressure	Helmet
4. M-32 Gradient	Oxygen Mask
5. Probe Gradient	Noise Shield
6. Probe Gradient	Helmet
7. M-33/AIC Gradient	None
8. Tooth	None
9. Probe Pressure	Noise Shield
10. Probe Gradient	Noise Shield
11. Forehead	Helmet
12. Ear	Harvintip and Muff
13. Probe Pressure	None
14. Forehead	None
15. Ear	Harvintip

TYPE		OPERATION	STRUCTURE
Space Vehicle		Takeoff	Double
Space Vehicle		Re-entry	Double
Space Vehicle		Takeoff	Single
Manned Aircraft		Takeoff	Canopy
Space Vehicle		Re-entry	Single
Manned Aircraft		Cruise	Canopy
Manned Aircraft		Low Alt.-High Speed Canopy	

KEY   SPEAKING EFFORT

Below Normal

Below Raised

Below Very Loud

Weighted Noise Level
(see text)

Speaking Effort . . . .

Normal . . . Raised . . . . . Very Loud

DIRECTIONS: Determine weighted noise level or operation. Draw vertical line at appropriate noise level. If the microphone system bar at the desired speaking effort lies to the right of the vertical line, the system will yield at least 90% sentence articulation score (see example in text).

CAPABILITIES OF SPEECH PROJECTION SYSTEMS IN NOISE

Figure 4

WEIGHTED NOISE LEVEL IN DECIBELS

RECEPTION SYSTEM

RECEIVER TYPE	COUPLING	NOISE EXCLUDER
Dynamic	Cavity	Clark Muff
Dynamic	Cavity	Liquid Seal Muff
Dynamic	Cavity	Doughnut Cushion
Miniature Dyn.	V-51R	V-51R
Miniature Dyn.	Harvintip	Harvintip
Dynamic	6-in. Tubing	V-51R and Helmet
Dynamic	Horn (WEAL)	Helmet
Magnetic	Horn (RCA)	Helmet
Magnetic	6-in. Tubing	V-51R
Miniature Loudspeaker	Mounted inside helmet	Helmet
External Loudspeaker	Air	Helmet

(Axis scale: 80, 90, 100, 110, 120, 130, 140)

KEY

☐ Capability limited by 95 db DRC

▨ Capability limited by Power Requirement or ear overload

Weighted Noise Level (see text)

TYPE	OPERATION	STRUCTURE
Space Vehicle	Takeoff	Double Wall
Space Vehicle	Re-entry	Double Wall
Space Vehicle	Takeoff	Single Wall
Manned Aircraft	Takeoff	Canopy
Space Vehicle	Re-entry	Single Wall
Manned Aircraft	Cruise	Canopy
Manned Aircraft	Low Altitude, High Sp.	Canopy

DIRECTIONS: Determine weighted noise level or operation. Draw vertical line at the appropriate noise level. If the reception system bar lies to the right of the vertical line, the system will yield at least a 90% sentence articulation score. (see example in text)

CAPABILITIES OF SPEECH RECEPTION SYSTEMS IN NOISE (see text)

Figure 5

MICROPHONE SYSTEMS

Figure 6

A. No Noise Shield

1. Forehead
2. W.E. 640AA Probe Pressure
3. W.E. 640AA Probe Gradient
4. M-33/AIC
5. Tooth Mic.
6. Ear Mic.

B. In Fiberglas Noise Shield

1. W.E. 640AA Probe Pressure
2. W.E. 640AA Probe Gradient

C. In MA-1 Helmet

1. Forehead
2. W.E. 640AA Probe Pressure
3. W.E. 640AA Probe Gradient
4. Tooth

D. Miscellaneous

1. M-34/AIC in MX 1334/U Noise Shield
2. Ear Mic. under D. Clark Muff

Not Shown: M-32 in MS22001 Oxygen Mask

SPEECH RECEPTION SYSTEMS

1. Raanwell H-136/AIC;
   Clark Muff
2. RCA H-143/AIC;H-158
   Muff
3. ANB H-1A; Harvard
   Doughnut
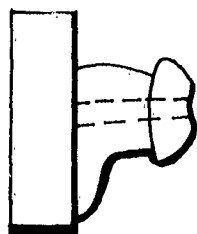
4. RCA Miniature; V-51R
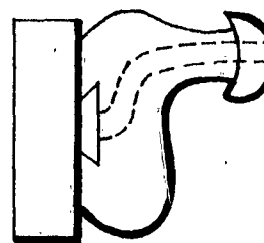
5. RCA Miniature;
   Harvintip
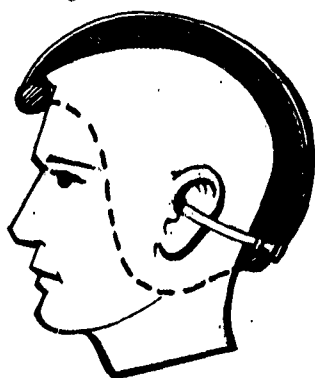
6. RCA H-143/AIC; 6-in.
   Tubing to V-51R and
   Helmet
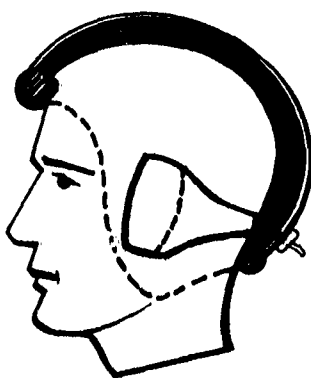
7. ANB-H-1A Horn
   Coupled to Ear (WEAL
   Fiberglas Horn) in
   Helmet
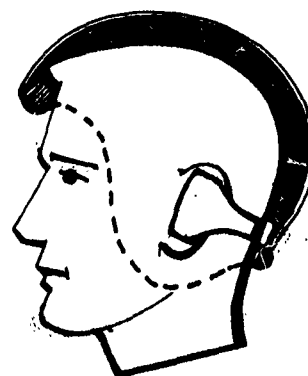
8. Dynalab Receiver Horn
   Coupled to Ear (RCA
   Plastic Horn) in Helmet
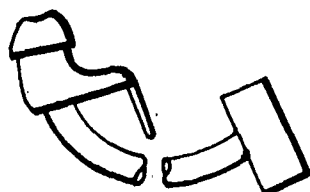
9. Telex Receiver;
   6-in. Tubing to V-51R
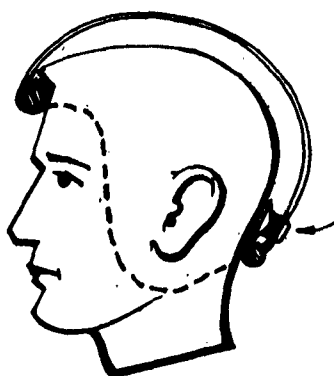
10. RCA Miniature
    Loudspeaker in Helmet
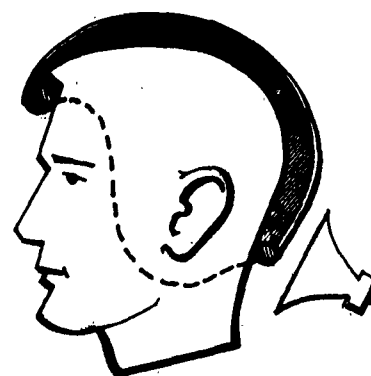
11. Loudspeaker External
    to Helmet

Figure 7

Figure 8

ATTENUATION REQUIRED TO ACHIEVE THE
CRITERIA OUTLINED IN FIGURE 8
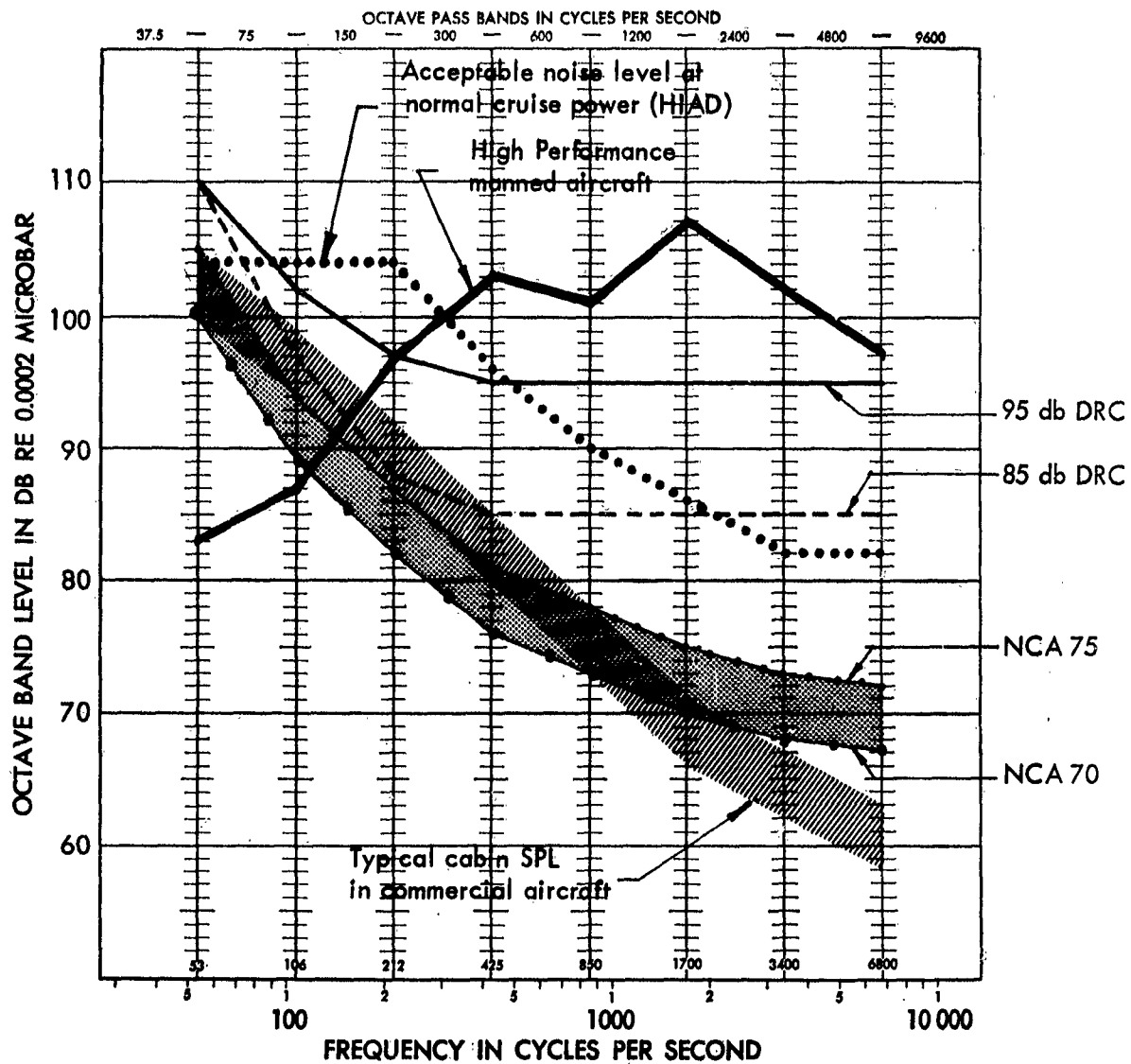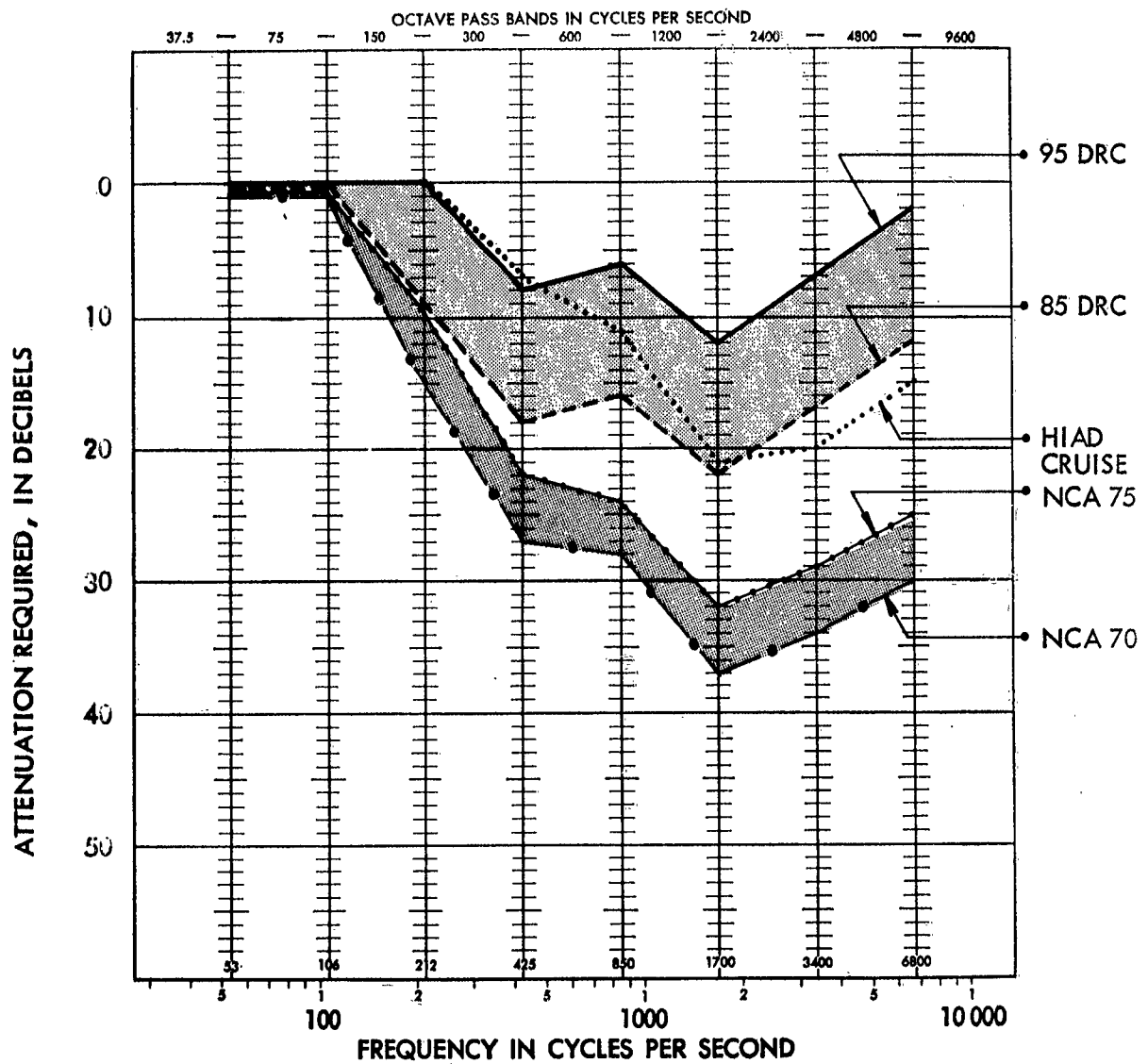
Figure 9

TOOTH VENEER
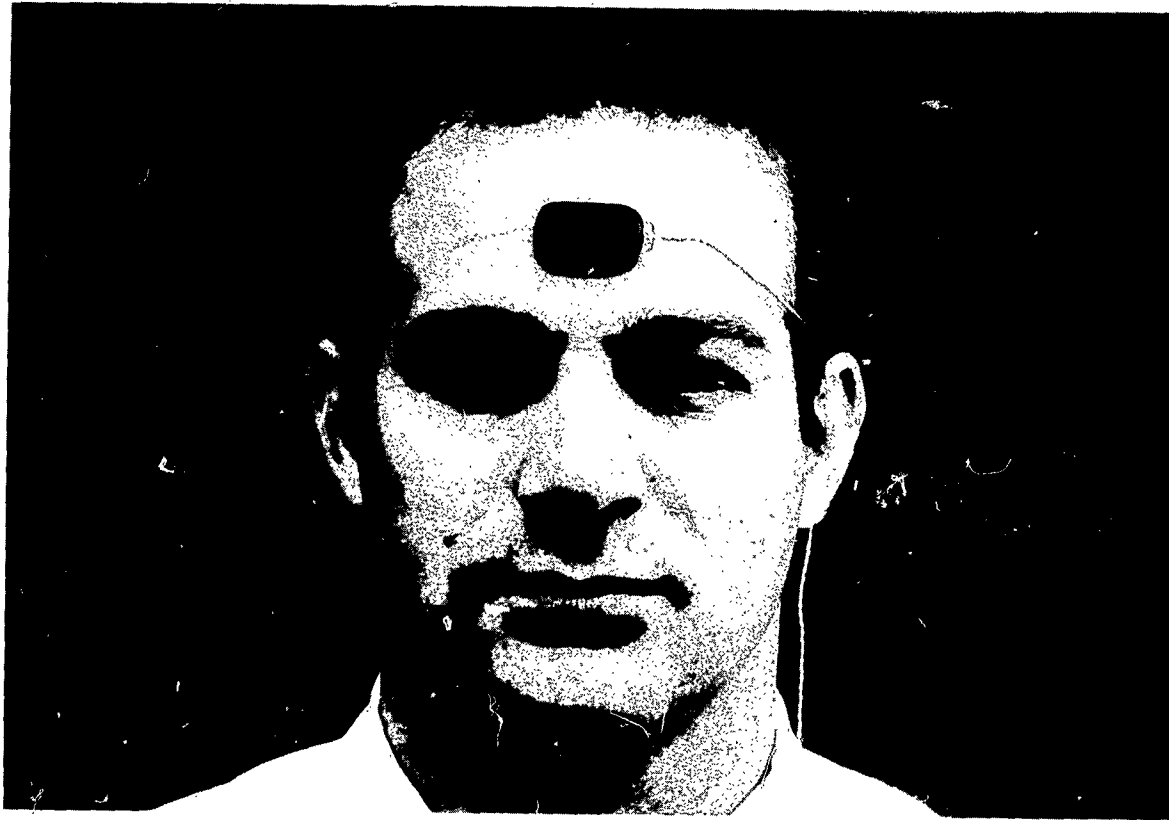
Figure 10

FOREHEAD MICROPHONE

Figure 11
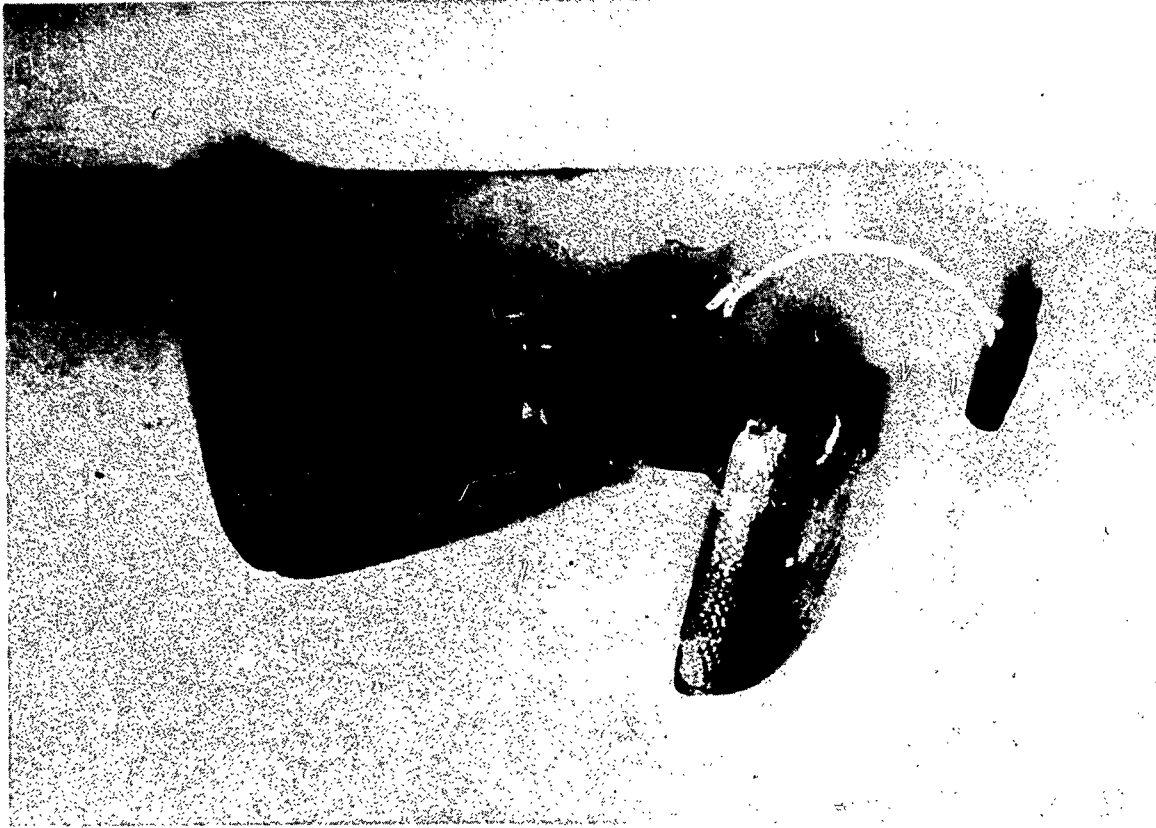
HORN COUPLED RECEIVER

Figure 12

LOUDSPEAKER IN PLASTIC HELMET

Figure 13

W. E. A. L. SEMI-INSERT EARPLUG
WITH MINIATURE RECEIVER

Figure 14

SENTENCE, PB WORD, AND CVC WORD ARTICULATION
PERCENTAGE VS SIGNAL-TO-NOISE RATIO

Figure 15

C-825A/A1C-10

TOOTH MICROPHONE PREAMPLIFIER

WEAL SEMI-INSERT EAR PROTECTOR WITH RECEIVER

ACCELEROMETER

TOOTH VENEER

SYSTEM NO. 1

Figure 16

C-82SA/AIC-10

HORN COUPLED RECEIVER
IN SOUND ABSORB HELMET

M-38/AIC
MICROPHONE

SYSTEM NO. 2

Figure 17

C-823A/AIC-10

FOREHEAD MICROPHONE
PREAMPLIFIER-EQUALIZER

WEAL SEMI-INSERT EAR
PROTECTOR WITH RECEIVER

FOREHEAD
MICROPHONE

SYSTEM NO. 3

Figure 18

C-825A/AIC-10

TOOTH MICROPHONE
PREAMPLIFIER

ACCELEROMETER

TOOTH VENEER

MM-2
LOUDSPEAKER

SYSTEM NO. 4

Figure 19

APPENDIX OUTLINE

Appendix Outline (continued)

Appendix Outline (continued)

5.0 Acoustic Feedback
    5.1 Summary
    5.2 General Analysis of the Feedback Problem
    5.3 General Conclusions
    5.4 Experimental Verification of Feedback Theory

6.0 Miscellaneous Studies
    6.1 Correlation of the Intelligibility of CVC and PB Words in Noise
    6.2 Sentences Based on Air Force Vocabulary for Use in
        Intelligibility Testing
        6.2.1 Purpose
        6.2.2 Source of Vocabulary
        6.2.3 Design of Sentences
        6.2.4 Training Period for Articulation Crew
    6.3 Relation Between Peak, Long Time Average, VU Meter Peak
        Levels for Speech
    6.4 The Limits of Ear Protection

APPENDIX I

PREDICTION OF MAXIMUM NOISE ENVIRONMENT
IN MANNED COMPARTMENTS OF VERY
HIGH PERFORMANCE AIRCRAFT AND SPACE VEHICLES

PREDICTION OF MAXIMUM NOISE ENVIRONMENT
IN MANNED COMPARTMENTS OF VERY
HIGH PERFORMANCE AIRCRAFT AND SPACE VEHICLES

1.1 SUMMARY

Predicted maximum spectra for the noise external to manned
compartments in very high performance aircraft and space vehicles are given
for both propulsion system noise and aerodynamic noise. These spectra are
translated into an internal noise environment for several types of assumed
compartment structure. Comparison of these predicted internal spectra with
measured spectra in subsonic Air Force turbojet aircraft shows that an increase
in internal noise level can be anticipated for these two types of future aircraft.
This increase is on the order of 10-15 db in the range of 600-4800 CPS relative
to subsonic aircraft, and the order of 0-5 db relative to the maximum noise in
the same frequency region in Century series fighter aircraft.

1.2 INTRODUCTION

The noise environment within manned aircraft and space vehicles
is one of the determining factors in the requirements for Air Force airborne communi-
cations systems. It is, therefore, of major importance in the development of these
communication systems that the noise environment be understood both to enable proper
system evaluation and to provide guidance for development programs.

Although the noise environment in present manned aircraft is well
documented, there are few measurements which are directly applicable to manned
space vehicles and to very high performance aircraft. As a result, the various
existing data and noise prediction methods have been utilized to enable an estimate
of possible future noise environments.

There are four major factors which control the airborne noise environment
inside manned aircraft and space vehicles. These are:

(a) Propulsion system noise;
(b) Aerodynamic noise generated in the boundary layer;
(c) Compartment noise reduction;
(d) Internal equipment noise.

Noise from rocket and jet propulsion systems is well known (Ref. 1, 2, 3),

and the noise external to a manned compartment can be computed with reasonable accuracy. The resulting noise environment within the compartment can be determined from the estimated or measured noise reduction of the shell of the personnel compartment.

Aerodynamic noise, generated in the boundary layer along the outer skin, has only recently come into prominence with the development of high performance aircraft. The results of a recent correlation of aerodynamic noise and aerodynamic parameters can be utilized to predict spectra for high performance aircraft and space vehicles.

The noise environments in many present Air Force aircraft are controlled by noise from internal systems such as defog, ventilation, pressurizing, etc. Future aircraft and space vehicles still may be plagued with these internal noise sources, and in addition, be subjected to noise generated by the vibration of retro and control rockets. However, it is not considered that this internal noise is fundamental to the system, as is the noise from the propulsion plant and boundary layer. Rather, it is felt that these internal noise sources can be controlled through application of conventional acoustical design practices to reduce their contribution to the noise environment below that of the more fundamental sources. Therefore, internally generated noise will receive no further consideration in this discussion.

1.3 PROPULSION SYSTEM NOISE

The major source of propulsion system noise is the turbulent mixing region between the turbojet or rocket jet stream and the ambient atmosphere. Other propulsion system noise, compressor whine, screech, rough burning, etc., may add to the environment, although for qualified flight power plants this noise is, in general, substantially below the maximum levels of the mixing noise.

Figure 1 gives some typical examples of the noise environment external to a manned compartment for a Century series fighter and for a hypothetical space vehicle at launch. Although both noise spectra are continuous and random, the space vehicle noise cone is subjected to higher noise levels throughout the frequency spectrum, particularly in the low frequency region. The resultant noise within these two compartments will be examined in a later section.

PROPULSION NOISE AT LAUNCH
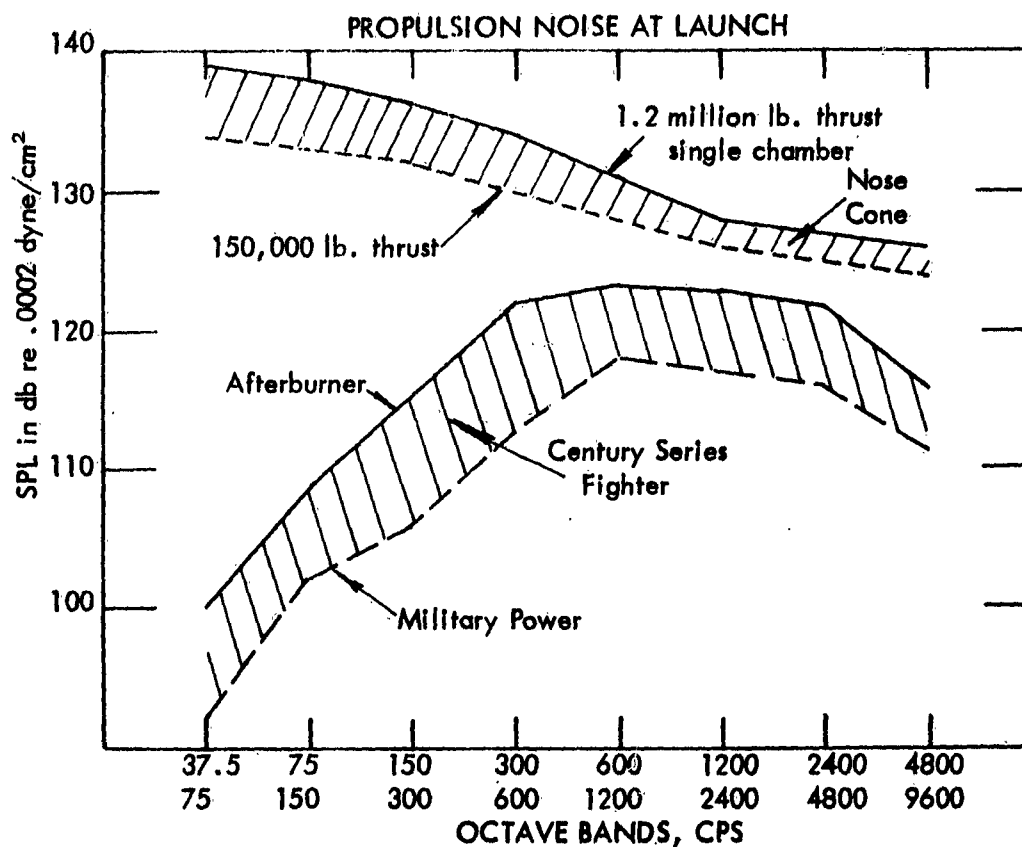
External Noise Exposure for Typical Single-Engined Fighter
Cockpit and Nose Cone of a 100-ft. Long Missile.

Figure A1-1

As stated previously, it is possible to estimate the noise levels at
launch external to any vehicle configuration from a knowledge of the major power
plant parameters from methods outlined in References 1 through 3. However, these
references do not enable prediction of the change of this noise which occurs as the
vehicle accelerates directly after launch. As the vehicle speed increases, the
total mixing noise energy is reduced because of a reduction of the relative velocity
between the jet stream and the surrounding atmosphere. In addition, the noise is
further reduced because the acoustic distance between the noise source in the jet
stream and any portion of the vehicle forward of the source is increased by the
increased time necessary for the sound to travel between the source and the vehicle.
Further, the development of a turbulent boundary layer around the vehicle tends
to diffract and attenuate the sound. Additional reduction will also occur as the
vehicle gains altitude and the air becomes less dense.

The calculated effects of the first two of these changes are given in Figure 2 for both the turbojet at military power and the typical rocket as a function of vehicle Mach number. The figure also shows several data points obtained from the nose cone of a 16-ft. rocket-powered missile. It is felt that the reason that these data show a greater decrease than predicted is that this nose is only 16 ft. forward of the nozzle and thus still in the near field of the rocket noise. Hence, the noise decreases at a greater rate with increasing distance than the 6 db per doubling of distance assumed in the figure for the far field. Further details regarding the derivation of Figure 2 are given in Reference 4.

Comparison of Calculated and Experimental Decrease of
Overall SPL for Positions in the Far Field forward of Engine
at Standard NACA Conditions
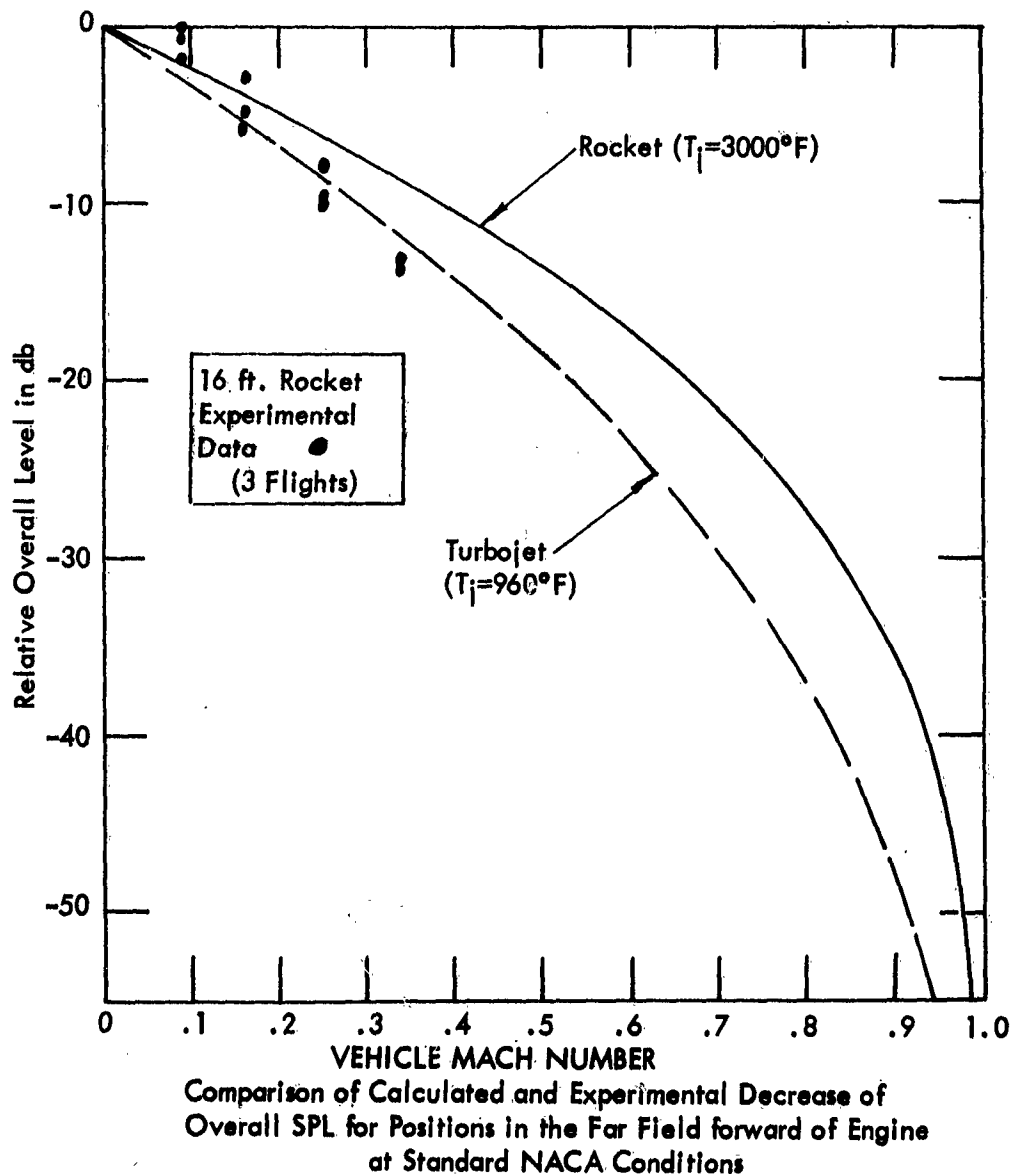
Figure A.1-2

As can be seen from the Figure, the noise level at any point forward of the jet nozzle tends to zero as the vehicle's velocity approaches Mach 1. Hence, for high performance vehicles the noise from the propulsion system is of interest only at takeoff or launch and through the initial subsonic portion of the mission profile.

IV. AERODYNAMIC NOISE

Although the propulsion noise external to manned compartments located forward of the engine was seen to decrease with increasing vehicle velocity, it is soon replaced by the generation of noise in the turbulent boundary layer. No general correlation of aerodynamic noise levels and spectra with pertinent aerodynamic parameters exists in the literature. However, the data in References 5, 6 and 7, together with other more recent unpublished data, have led to the development of a method for predicting aerodynamic noise.
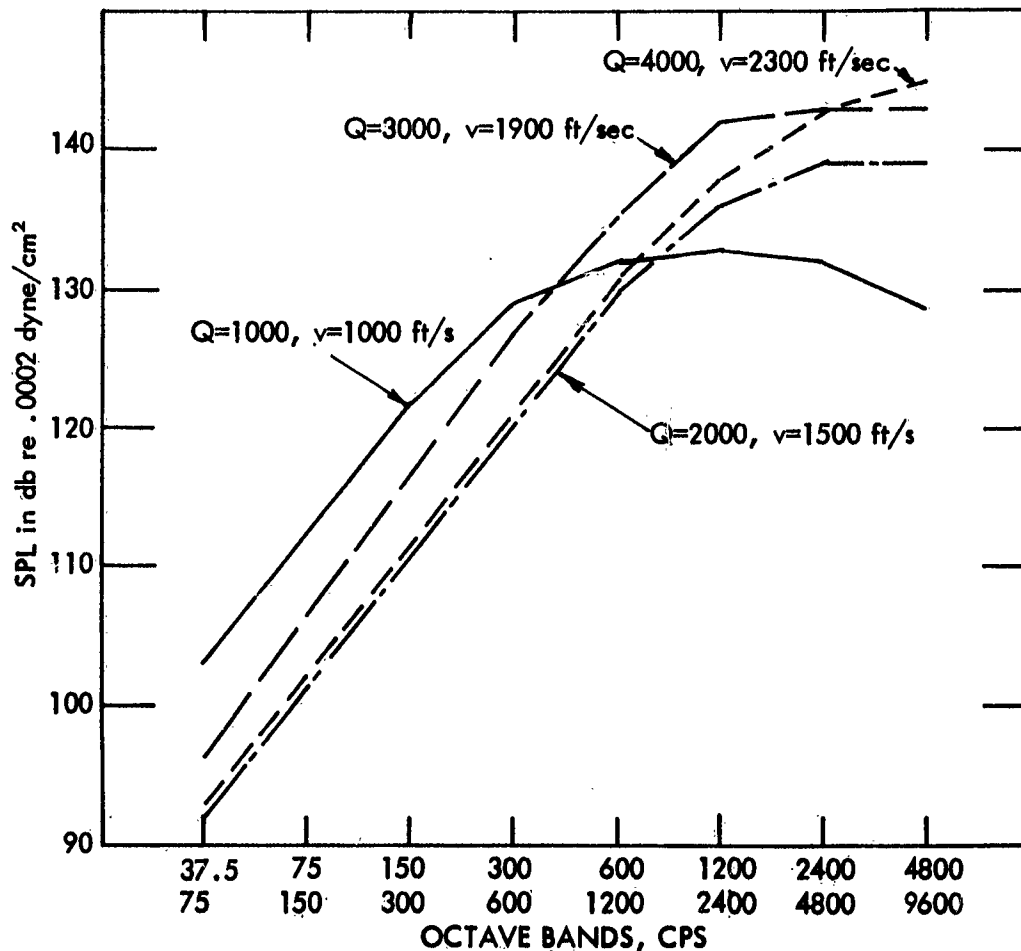
Some Typical Predicted Aerodynamic Noise Spectra for a Position External to a Missile Nose or Canopy Windshield for the Indicated Local Aerodynamic Conditions.

Figure A1-3

This method, which will be published by WADC (WCLDN) has been used to predict the external noise spectra given in Figure 3. These spectra are believed to be typical of maximum conditions which will be encountered external to a manned space vehicle compartment or the cockpit of a very high performance aircraft. As can be seen from the Figure, the spectra all tend to rise steeply from the low frequency region to their maximum values at frequencies above 600 CPS.
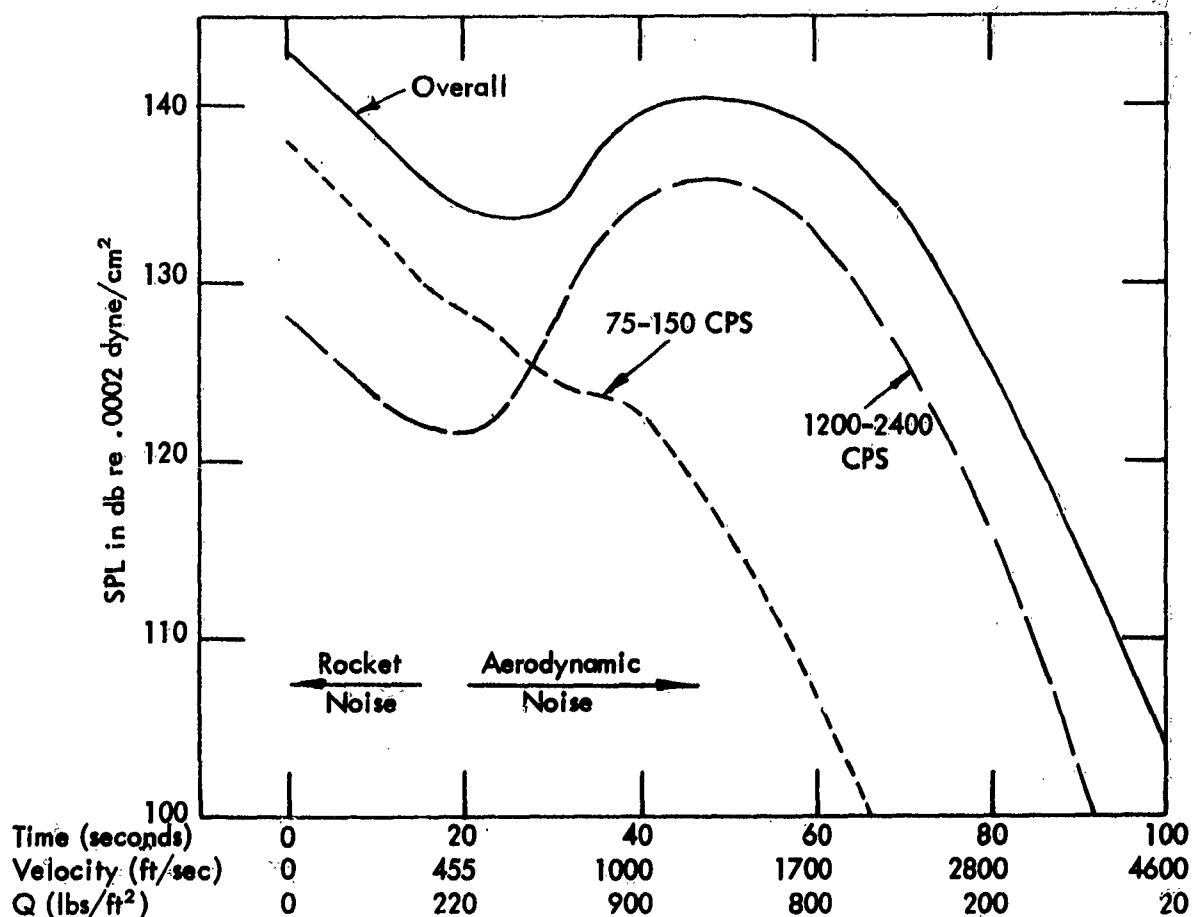
Note that these spectra are computed for forward positions on the vehicle. In general, the noise spectra external to unmanned compartments located farther aft would be higher in level and contain relatively more low frequency energy. Although these spectra have been chosen to be representative of four distinct and separate aerodynamic conditions their range is considered indicative of possible spectra at other intermediate conditions. Spectra predicted for lower Q vehicles are generally lower in overall level than those shown, although they may contain relatively more low frequency energy.

Time (seconds)	0	20	40	60	80	100
Velocity (ft/sec)	0	455	1000	1700	2800	4600
Q (lbs/ft²)	0	220	900	800	200	20

Example of the Change of External SPL in Selected Frequency Ranges with Time for a Possible Manned Vehicle Launch Profile. Thrust is 1.2 million lbs., Nose Cone is 100 ft. Forward, Freestream Q Maximum is 1000 lbs/ft².

Figure A1-4

Figure 4 gives an indication of the change in noise external to a manned space vehicle which reaches a maximum free stream dynamic pressure Q of 1000 lbs/ft² at 50 seconds after launch. In this Figure the overall SPL, which is determined by propulsion system noise at launch, decreases with increasing vehicle velocity in accordance with Figure 2. However, at about T = 25 seconds the overall SPL begins to rise because of the increase of aerodynamic noise. This rise continues until the maximum local Q is reached. Then the noise decreases as the vehicle accelerates into less dense atmosphere. The behavior of the noise in the 1200-2400 CPS frequency band is seen to be similar to the overall curve, although it reaches its maximum prior to 50 seconds. This results from the increasing shift of noise energy to higher frequencies as the vehicle's speed increases. The noise in the low frequency 75-150 CPS octave band also decreases in accordance with Figure 2, until about 20 seconds, where the addition of aerodynamic noise slows the rate of this decrease. During reentry it is understood that the maximum free stream dynamic pressure will be on the order of 3000 to 4000 lbs/ft² for a hypersonic glide reentry vehicle. However, the maximum Q for a low weight, high drag capsule could be as low as the order of 50-100 lbs/ft². Because the major interest in this discussion is determination of realistic maximums, the maximum aerodynamic noise external to the manned compartment space vehicle will be considered that calculated for a hypersonic reentry Q of 3000 lbs/ft².

1.5 NOISE REDUCTION

The preceding sections have developed estimates of noise spectra external to manned compartments for space vehicles and high performance aircraft. However, these estimates are useless for determining the internal environment unless some estimate can be formed of the noise reduction of the structure between the external and internal space. Unfortunately, it is impossible to generalize this noise reduction because it depends upon the individual structural configuration. However, for the purpose of determining reasonable estimates of the internal noise environment some extrapolations of noise reduction can be made from current design experience.

Figure 5 gives the estimated noise reduction for three types of possible compartment structure. The curve given for an optimum bubble canopy is considered applicable to aircraft with single 3/8-in. thickness of transparent material. Its noise reduction departs from the conventional mass law assumptions because of stiffness in the low frequency region, and is limited by coincidence effects in the speech frequency region. Note that this noise reduction estimate assumes an average absorption coefficient of .35, which considerably exceeds that found in present day fighter aircraft. Hence, the estimate represents optimum values which can be achieved only by determined design effort.

Noise Reduction Calculated for Three Assumed Structures.
Absorption Assumed as .35.
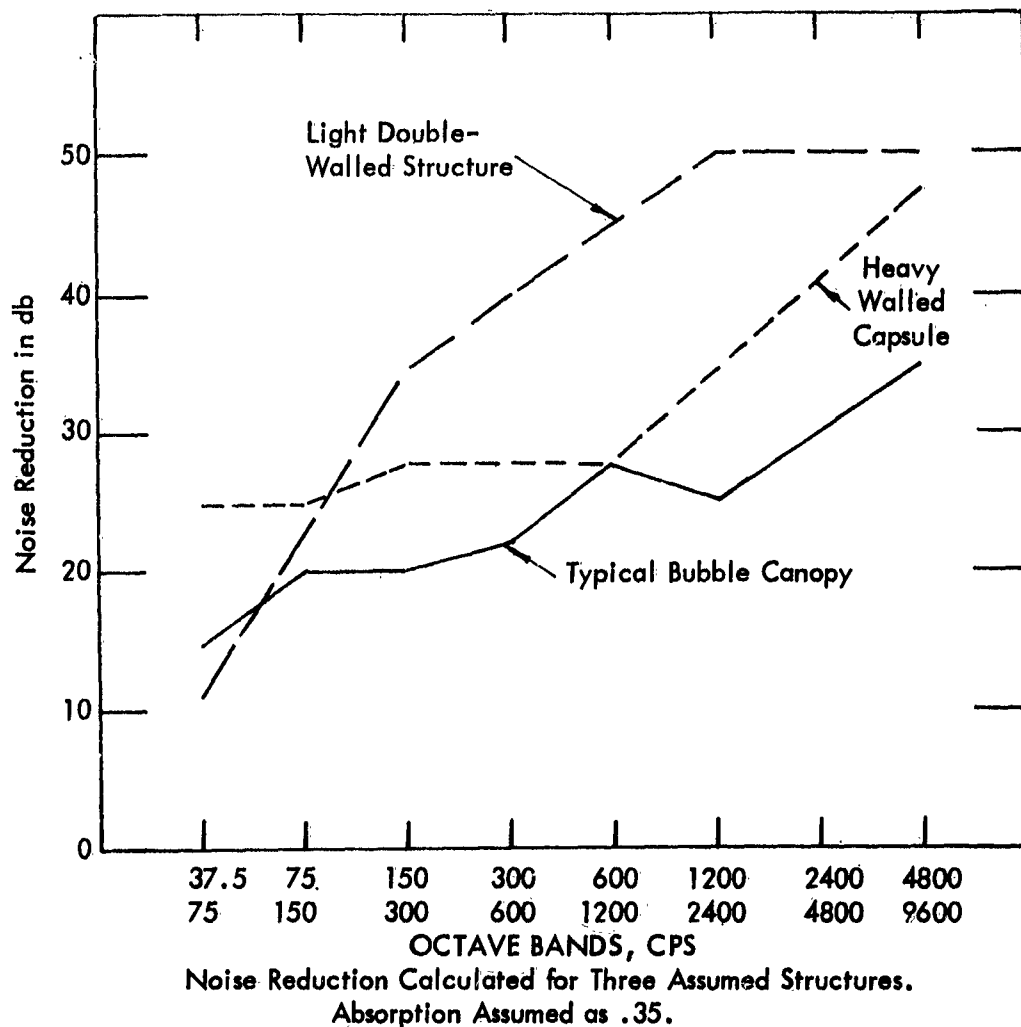
Figure A1-5

The curve given for the heavy walled capsule is developed for a 3/4-1 in. single thickness of copper. It also exhibits the estimated effect of stiffness control at low frequency and coincidence in the 600-1200 CPS band. The third structure is a double thickness of .02 in. steel, separated by a 1 in. thickness of Fiberglas and a mechanical connection, which gives a resonance for the two skins of about 25 CPS. Because of the 25 CPS resonance, this double structure exhibits less noise reduction in the very low frequencies than do the other two structures. However, above 150 CPS its superior noise reduction becomes evident.

It is not intended that the noise reduction estimates for these three structures represent all possible structures, for this is clearly impossible. Rather, it is hoped that these noise reduction estimates represent a reasonable performance range for structures which

can be provided for future high performance aircraft and manned space vehicles, and thus allow estimation of the resultant maximum internal noise environment.

1.6 INTERNAL NOISE ENVIRONMENTS

Figure 6 gives the predicted internal noise within the canopy of a manned high performance aircraft. The figure is developed from the external noise for takeoff given in Figure 1, the external noise at high dynamic pressures in Figure 3, and the noise reduction for the bubble canopy in Figure 5. As can be seen, the maximum internal noise results from aerodynamic noise and will occur during high speed low altitude flight.
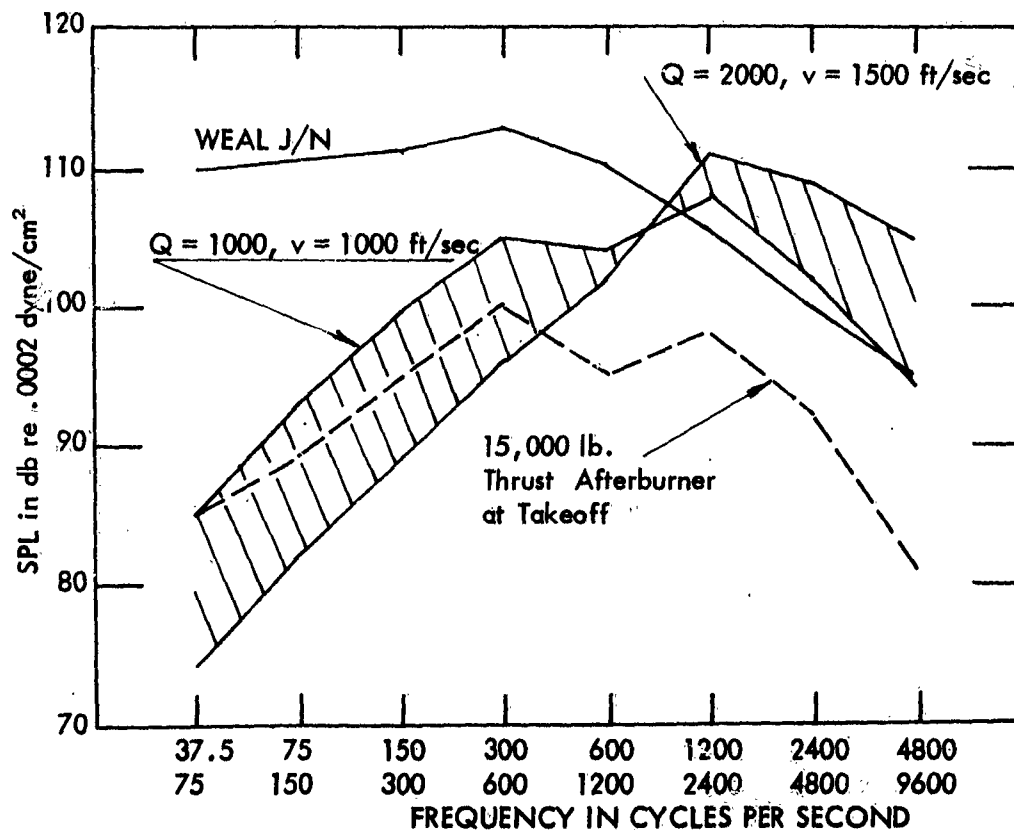
Comparison of Internal SPLs estimated Inside Canopy of Manned Aircraft for the Stated Conditions for Noise Reduction of Bubble Canopy (from Figures 1, 3 and 5)

Figure A1-6

Figure 7 gives a similar presentation for the launch and reentry phases of a manned space vehicle. Here the predicted noise environment from the propulsion system has a steeply sloping spectrum from the order of 120 db in the 37–75 CPS frequency band to 78 db in the 4800–9600 CPS band. The internal spectrum from aerodynamic noise generation, estimated for hypersonic reentry, is almost the inverse of the propulsion noise spectrum, and has its maximum values in the middle of the speech communication frequency range. The limits shown for each of these two types of noise result from the two noise reductions obtained from Figure 5.
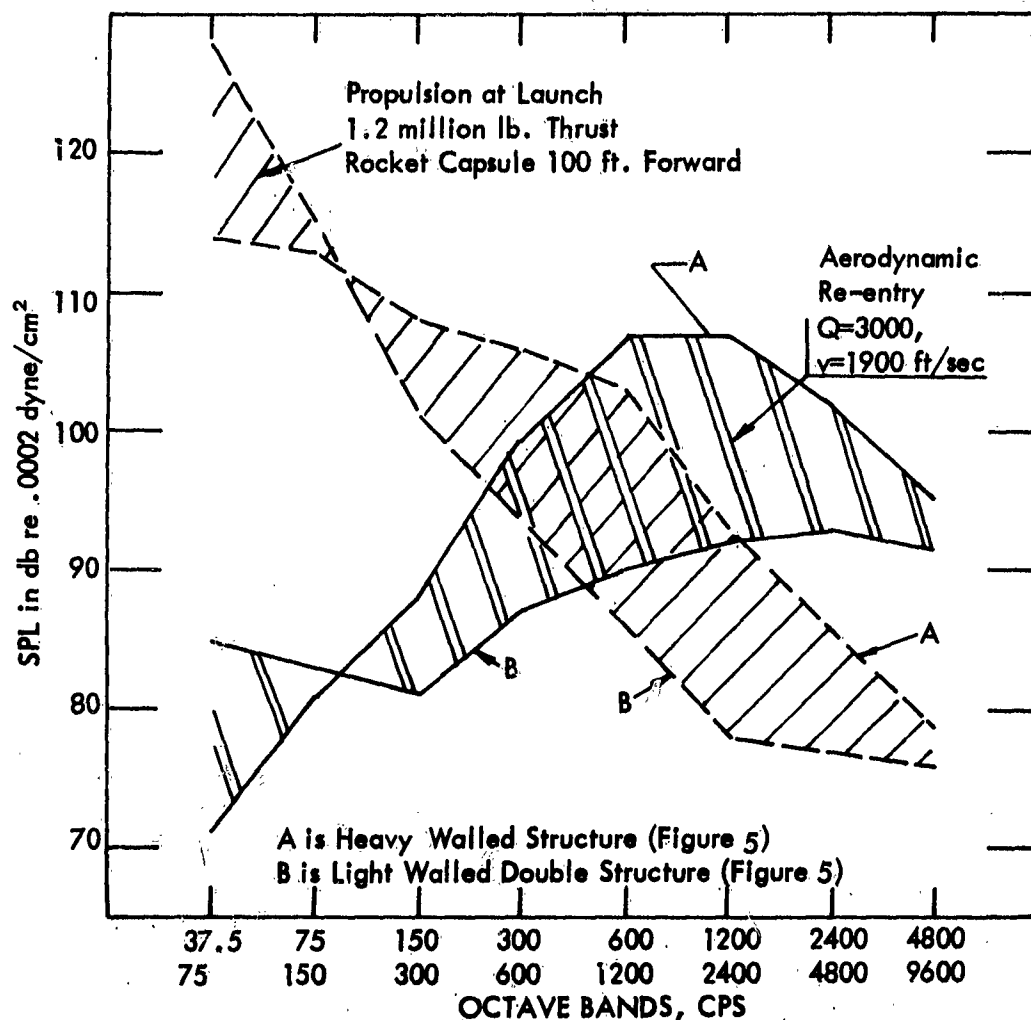
Comparison of Maximum Internal SPLs Estimated
Inside Space Vehicle Capsule for Two Values of
Noise Reduction and for the Stated Conditions
(from Figures 1, 3 and 5).

Figure A1-7

The internal noise spectra for both types of vehicles are compared in Figure 8 to the measured spectra in typical high subsonic Air Force turbojet aircraft (Ref. 8). Here it becomes clear that the low frequency noise levels expected during launch of a manned missile with 1.2 million pounds thrust are considerably above the levels encountered with jet aircraft of 15,000 lbs. thrust. Further, these low frequency levels for the manned vehicle are on the order of 10 db above those usually encountered in propeller aircraft (see Ref. 8).
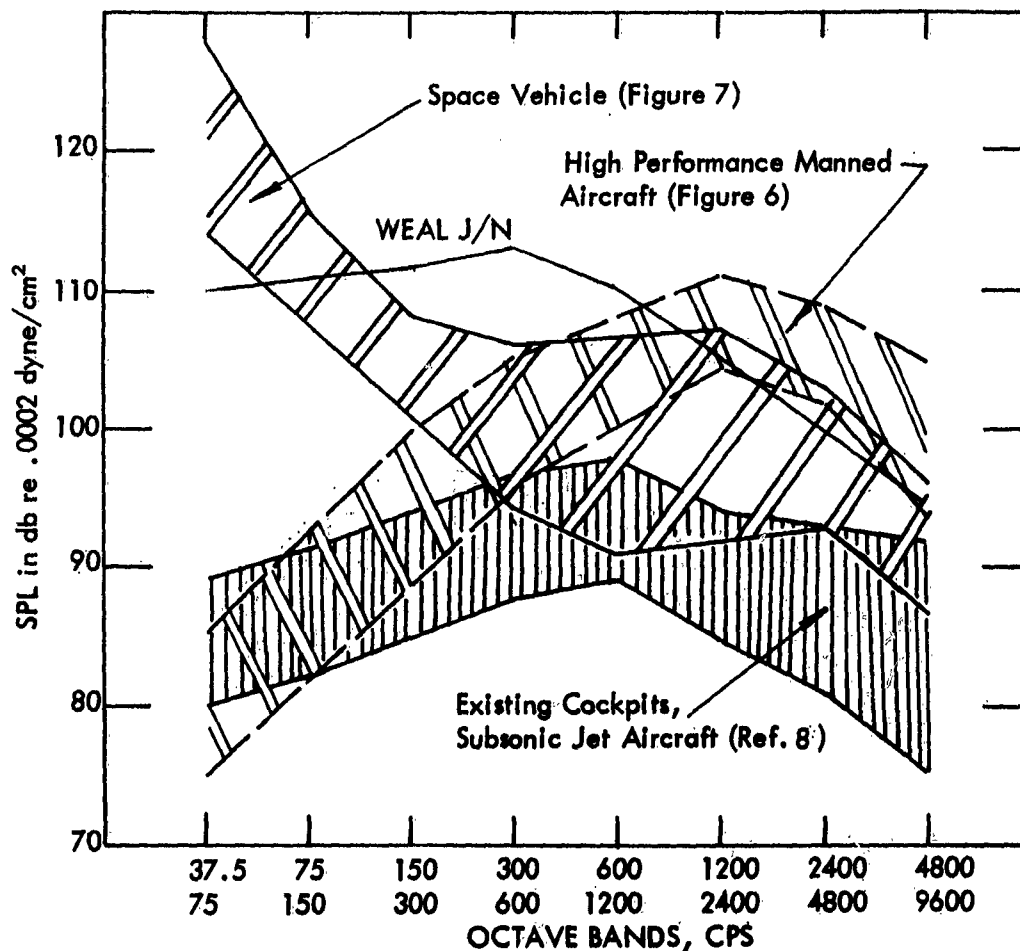
Comparisons of Maximum Predicted Noise Spectra in Space Vehicle and High Performance Aircraft with Data from Subsonic Air Force Turbojet Aircraft. Contributions from Internal Noise Sources are not included.

Figure A1-8

A1-11

The estimated noise levels in the frequency range most important for speech, 600–4800 CPS, are above those encountered in present subsonic turbojet aircraft. However, the noise in some present high performance aircraft resulting from aerodynamic turbulence, does approach the values predicted for very high performance aircraft. It should be noted that the predicted aerodynamic noise in the high performance aircraft exceeds that predicted for manned space vehicles because of its lesser noise reduction resulting from the thin single shell canopy.

1.7 CONCLUSIONS

Disregarding internal noise sources from various auxiliary equipment, two external noise sources dominate the internal noise environment for manned space vehicles and high performance aircraft. Directly at launch or at the beginning of takeoff roll the noise from the propulsion system is maximum. This noise decreases as the vehicle's speed increases, until at some vehicle velocity the propulsion noise is overshadowed by aerodynamic noise generated by boundary layer turbulence. This aerodynamic noise increases with increasing vehicle velocity until the maximum mission Q has been reached.

The internal noise of aerodynamic origin is maximum in the speech frequency range of 600–4800 CPS. The maximum internal noise level in this frequency range is expected to be between 100 and 110 db SPL in the cockpit of high performance aircraft which have single transparent canopies and optimized absorption. Further, the noise level in this frequency range is anticipated to be on the order of 92 to 107 db in the capsule of a manned space vehicle at maximum anticipated launch or reentry local Qs of 3000, depending upon the construction of the capsule. It is noted that these levels will be increased if the noise reduction achieved by design does not equal that estimated in Figure 5.

The internal noise during launch or takeoff resulting from the propulsion system will be less in the speech communication frequency range than the level resulting from the maximum aerodynamic noise. However, occupants of high thrust manned space vehicles will be subjected to a large increase of low frequency noise directly at launch. This predicted low frequency noise considerably exceeds the low frequency levels encountered in present aircraft, and will contribute to the masking of speech communication.

REFERENCES

1. von Gierke, H. E., Chapter 33, "Handbook of Noise Control" McGraw-Hill

2. Callaghan, E.E. and Coles, W. D.: Far Noise Field of Air Jets and Jet Engines.   NACA Rept. 1329.

3. Howes, W. L. and Mull, H. R.: Near Noise Field of a Jet Engine Exhaust, I – Sound Pressures. NACA Rept. TN 3763.

4. Eldred, K. M. et al: Prediction of Rocket and Turbojet Noise, presented at 52nd Meeting of Acoustical Society of America 15 November 1956.

5. Rogers, O. R. and Cook, R. F.: Aerodynamic Noise and the Estimation of Noise in Aircraft. WADC TR 52-341.

6. Mull, H. R. and Algranti, J. S.: Preliminary Flight Survey of Aerodynamic Noise on an Airplane Wing. NACA RM E55K07.

7. Nelson, W. L. and Alaia, C. M.: Aerodynamic Noise and Drag Measurement on a High-Speed Magnetically Suspended Rotor. WADC TR 57-339, ASTIA AD 142153.

8. Noise Levels in Propeller and Jet Aircraft, WADC (WCRDB-5) Figure for Record of May 1956.

APPENDIX 2

ARTICULATION TEST EVALUATION
OF COMMUNICATION SYSTEMS IN NOISE

2.1 Summary

Articulation testing in a noise field was performed on useful combinations of speech projection and reception systems.

The following systems were evaluated with both the talker and the listener in a noise field:

System	Microphone	Receiver	Ear Protection
1	Tooth	Dynalab D-58	WEAL Semi-Insert
2	M-33/AIC	ANB-H-IA Horn Coupled	Bill Jack Sound Absorb
3	Forehead	Dynalab D-58	WEAL Semi-Insert
4	Tooth	External Loudspeaker, Universith MM-Z	Bill Jack Sound Absorb

These combinations were based upon potential application and considerations such as acoustic feedback.

Articulation testing was performed using special test material representative of Air Force communications. Both the talker and listener were in a jet noise spectrum shown in Figure 1. The results of the testing are as follows:

System	Overall Masking Noise, in db	Score
1	120	96
2	120	94
3	110	96
4	120	66
4	110	89

2.2 Choice of Systems

The choice of microphones and receivers was based upon recommendation 12 in the final report of the exploratory program. These systems were studied further and refined in Phase II. In the exploratory phase, these systems were evaluated separately, i.e. microphones were evaluated with the talker in noise and the listener using high quality headphones in a quiet environment. Similarly, reception system capabilities were defined using an articulation index computation which assumed the speech was picked up from a high quality microphone used in quiet surroundings.

Since in actual use we may expect both the talker and listener to be in a noise field, in Phase II articulation tests were performed on specific microphone-receiver combinations, with both the talker and listener in the noise. The systems

were used with interphone control C-823A/AIC.

A total of 3 microphones and 3 receivers were involved. Therefore, 9 separate systems could have been assembled from the 6 devices. However, some combinations are illogical for a variety of reasons. For example, the forehead microphone would not be used with an external loudspeaker because of a potential acoustic feedback problem. Four systems were finally chosen. These were previously listed in the summary.

Further description of the components in these systems may be found in Sections 4 and 5 of the Appendix.

2.3 Test Material

It was our aim to perform the articulation testing under as nearly as possible operational conditions. Hence, articulation testing material was chosen incorporating terms and phrases typical of U.S. Air Force communication. The background on this material is given in Section 7. Suffice it to say here that these words were assembled into sentences containing an introduction, such as "How do you read?"; a message such as "Bearing +2°N" and a closing, such as "Roger." The sentences and phrases were formed so as to stress recognition of a limited vocabulary and to otherwise minimize rote and contextual memorization. In other words, the recognition of one word in the sentence will not furnish a clue to correct identification of other parts of the sentence, even though they are not perceived .

2.4 Test Procedure

T

A schematic of the testing apparatus is shown in Figure 2. A separate monitoring system enabled the talker to establish a "raised level," i.e. 9 db above normal conversational level. All material was recorded and later played back to a listener in the same noise field. Two talkers and three listeners were employed. The testing crew was thoroughly familiar with the basic vocabulary and any standard procedure accompanying the words, as, for example, the fact that "bearing" is followed by angle and direction. The listener was allowed to control his level by adjusting the interphone volume control.

2.5 Results

The results are summarized in Table I. Also included is the long time average signal-to-noise ratio in the microphone channel, and the long time average power delivered to the reception system.

TYPICAL ARTICULATION TESTING MATERIAL

1. LBD, request glidepath speed, take over.

2. AB-10, cockpit check request, take over.

3. Repeat, adjust speed 150 miles, out.

4. Request, request taxi instructions, over.

5. Roger, request takeoff instructions, how do you read?

6. Acknowledge, range +85° north, over.

7. Roger, glidepath speed 122 miles, repeat.

8. ELNF, course 5° east, over.

9. TCA, glidepath speed 120 knots, roger.

10. How do you read? Glidepath on 97.5 megacycles, read back.

11. Read back, below rante + 14° north, repeat.

12. YMRE, repeat cockpit check, roger.

13. Roger, bearing +14° north, altitude 13 angels, repeat.

14. Commence, identified 99.9 megacycles, how do you read?

15. NPR, obstacle check request, out.

16. Permit, takeoff instructions completed, how do you read?

17. 389, Touchdown 4500 feet, over.

18. LBD, Bearing +92° north, out

19. KOZ, taxi instructions completed, over.

20. AB-10, restrict landing instructions, how do you read?

TABLE A2-I

SUMMARY OF COMMUNICATION SYSTEM ARTICULATION TESTING

Microphone	Receiver	Ear Protection	Score₁	Masking Noise₂	S/N₃	Power₄
1. Tooth	Dynalab D-58 Miniature Hearing Aid Type	WEAL Semi-Insert	96%	120	+13	-40
2. First order gradient M-33/AIC	Fiberglas Horn	Bill Jack Sound Absorb	94%	120	+13	-26
3. Forehead Sonotone 0-1	Dynalab D-58 Miniature Hearing Aid Type	WEAL Semi-Insert	96%	110	-2	-37
4. Tooth	External Loud-speaker University MM-2	Bill Jack Sound Absorb	66% 89%	120 110	+13 +13	+10 0

Notes:
1. % of key words correct
2. Overall level of masking jet noise
3. Signal-to-noise ratio in microphone channel (long time average Signal/Long time average noise)
4. Long time average power dissipated in receiver in db re 1 watt

WEAL JET NOISE TEST SPECTRUM USED IN
ARTICULATION TESTING.

OCTAVE PASS BANDS IN CYCLES PER SECOND

| 37.5 | — | 75 | — | 150 | — | 300 | — | 600 | — | 1200 | — | 2400 | — | 4800 | — | 9600 |

Figure A2 - 1

Ampex 350 tape recorder

C-823A/AIC

C-823A/AIC

Equalizer

Reception system under test

VU Meter

WE 640AA

C. M. C.

Monitor System

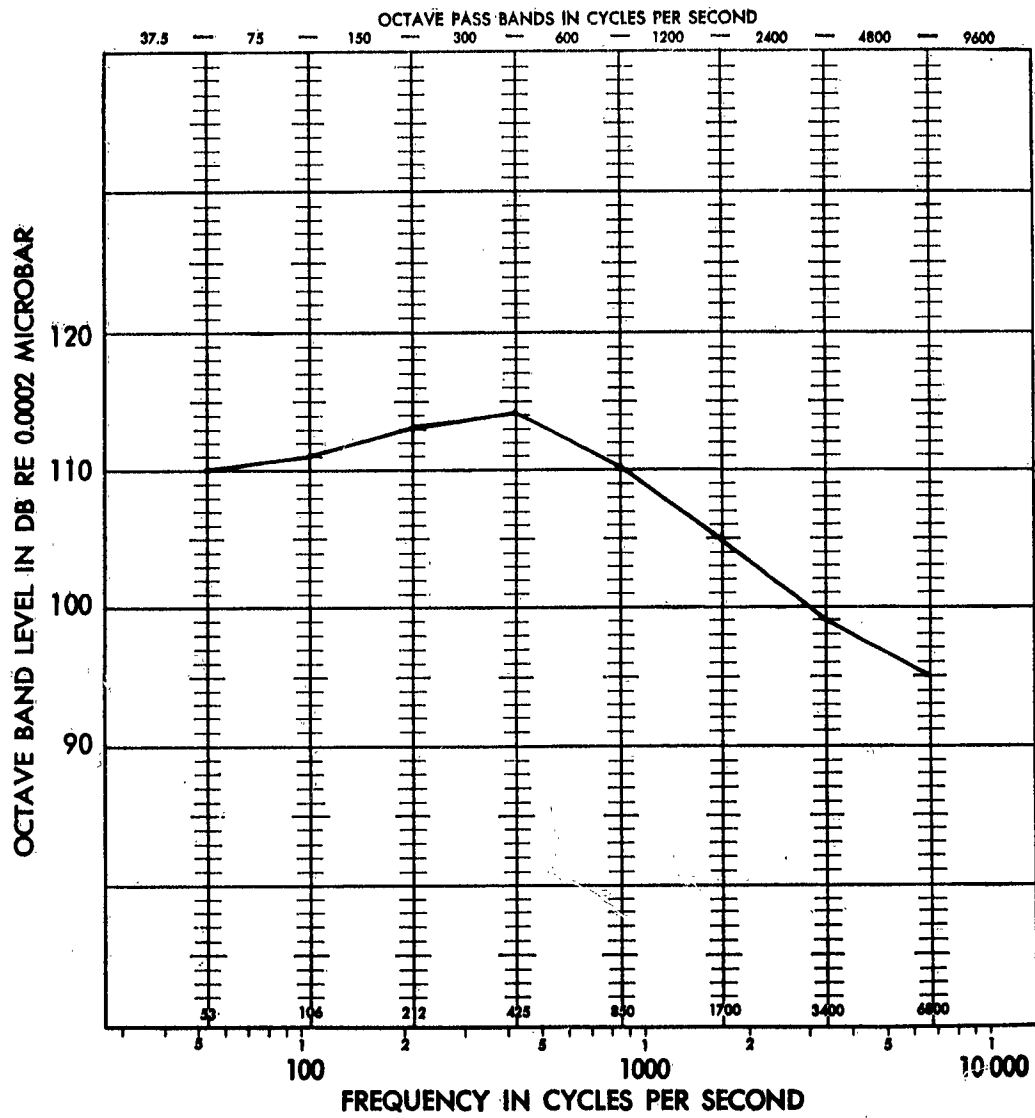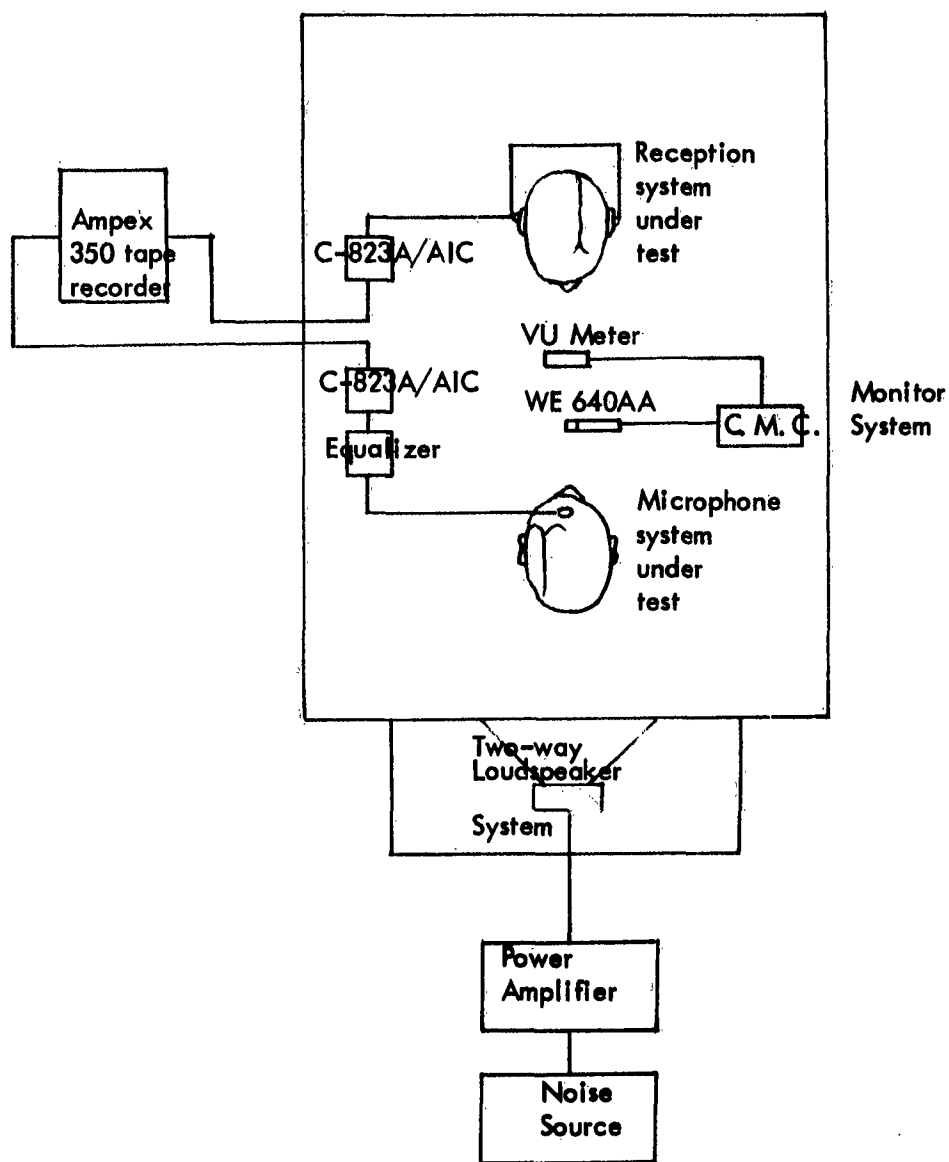Microphone system under test

Two-way Loudspeaker System

Power Amplifier

Noise Source

ARTICULATION TESTING APPARATUS

Note: In actual test, talker and listener were not in the room at the same time. They are shown together above only for convenience.

Figure A 2 - 2

APPENDIX 3

MICROPHONE DEVELOPMENT

3.1 Tooth Microphone

3.1.1 Introduction

One of the results of the exploratory program was the discovery that intelligible speech could be picked up on the front teeth. The device was also found to be extremely useful in high noise fields yielding intelligibility equal to a first order gradient microphone. The mounting device consisted of a band of brass surrounding one of the upper central incisors.

In this section a new mounting device, the "tooth veneer," is described, which was developed during the program extension. The veneer is a custom fitted device, but possesses advantages such as ease of retention, comfort, and eventual space for apparatus to transmit speech from the accelerometer on the tooth to outside the helmet, thus eliminating the necessity of a lead between the accelerometer and amplifiers.

3.1.2 Development of the Tooth Veneer

The first phase of the tooth microphone development was to design a practical mounting scheme. Two requirements were paramount: (1) 40-hr. wearability; (2) universal fit is highly desirable. However, a simple custom-fitted device should receive consideration.

As a first step we contacted Dr. R. E. Groetzinger, Westwood oral surgeon, with our problem of mounting schemes. He had been most helpful with our initial attempts at mounting the accelerometer on a tooth. Here is a brief summary of our conference with him.

(1) The current state of the art of orthodontia would allow the accelerometer to be mounted in almost any position. However, the use of orthodontic bands would surely require custom fitting and continued use would shift the position of the teeth in the mouth, with attendant pain. If the continuous wearing time were not excessive, the teeth will shift back into their natural positions after the device is taken off. It must be kept in mind that the teeth are normally continually shifting in their position.

(2) The use of a band around a single tooth, although having a prospect of being semi-universal (would require several sizes), has several disadvantages: (a) the taper of the front teeth makes a solid contact difficult; (b) the space between the front teeth may not allow a band to be slipped up over the tooth. A small slit, however, could be made between the teeth with little difficulty.

(3) The use of new adhesives developed for dental use may permit mounting directly on a tooth or a group of teeth.

(4) A mounting fitting over the gum and front teeth was suggested. This scheme appeared quite promising, so a sample was made in the dentist's office after the conference. It is more fully described below.

A thin veneer of quick-curing plastic was formed over the gums and the front teeth in the upper jaw. This process is accomplished very simply and quickly. It covers the incisors, canine and first bicuspids. A 3-48 machine screw was imbedded into the veneer to facilitate mounting the accelerometer. The device is held in place by the upper lip and adhesian due to saliva. The present device may be moved about within the mouth with the tongue. It is shown in Figure 1.

The quick-curing plastic material shrinks somewhat while it is hardening on the teeth. The process is exo-thermic; hence the veneer was removed before it was completely hardened to avoid burning the mouth and gums. Therefore the finished veneer does not fit perfectly against the teeth. In spite of this fact, the veneer is easily retained in the mouth and presses firmly against the teeth.

Of the three subjects fitted, two had relatively straight teeth, while one had a protruding canine. The retention was particularly good on this subject, indicating that crooked teeth will aid the fit as the veneer "locks" over the protruding teeth.

A cast of the upper jaw of each subject was made after each subject was fitted for the veneers described above. Later, veneers were formed over these castings. The material used was the same as used in dentures; there was no shrinkage. These veneers can also be made thinner and more uniform than those formed directly on the subject's teeth. They are shown in Figures 1, 2 and 3.

3.1.3 Optimum Mounting Position of Accelerometer on Tooth Veneer

Tape recordings were made to determine whether the output of the accelerometer was a function of mounting position on the tooth veneer. Three machine screw nuts were embedded along the tooth veneer. Long time average: for a constant speech effort is shown in Figures 4, 5 and 6. Two subjects, MG and JPC, showed slightly more output and improved quality with the accelerometer mounted in position #2, while JCO required mounting in the central position #1. Mounting in position #2 is also favorable to the others, since it restricts the movement of the upper lip to a lesser extent.

3.1.4 Comparison of Speech Output of Veneer and Tooth Bands

A comparison of the output of the accelerometer as mounted on the veneer and tooth bands was made. Results are shown in Figure 7 for two subjects. 1/6 octave analysis of speech spectra measured on the tooth bands and veneers is shown in Figures 8 and 9.

Approximately the same LTA speech level is obtained for both mounting configurations. The accelerations as measured on several teeth for the same speaking effort are shown in Figure 10 for one subject.

3.1.5 Effect of Mounting and Position on the Output of the Tooth Microphone in an External Noise Field

Measurements were made to determine the output of the tooth microphone in an external noise field when mounted on the tooth band and tooth veneer. In these measurements the subject was seated in a noise chamber and 120 db jet noise was introduced. The subject opened his mouth as to voice "a" in all the tests, since the output of the accelerometer is a function of mouth opening. The accelerations as measured on individual teeth are shown in Figure 11. The accelerations as measured using the tooth veneer are shown in Figure 12. One finds that approximately the same output is obtained from the bands and veneer.

Combining these results with those of Section 3.1.4 we find that the S/N ratio is approximately the same when either the tooth veneer or tooth bands are used.

3.1.6 Comparison of Speech Quality of Tooth Microphone and High Quality Pressure Microphone

Simultaneous recordings were made of the tooth microphone and 640AA pressure microphone with a two-channel tape recorder. The reading material consisted of CV and VC words consisting of all the consonants and the vowels A, I, U. Both the tooth band and tooth veneer were used. Listening to the recordings showed that there was no appreciable distortion of any of the speech sounds with either the tooth bridge or tooth veneer. However, on both attachments the vowel A was diminished. These recordings were made for only one subject, MG.

3.1.7 Encapsulation of Tooth Veneer

We are in the process of searching for an appropriate material for encapsulation of the body of the accelerometer and part of the cable. This material will protect the accelerometer from moisture as well as add strength to the cable attachment.

3.1.8 Lower Jaw Mounting of Tooth Veneer

It has been suggested that the tooth veneer be mounted on the lower jaw. This position is attractive because retention may be better. A veneer was made for one subject, MG. With no accelerometer mounted, the veneer poses no wearability problem. However, when the accelerometer is attached, the lower lip is distorted where it must bulge out around the accelerometer case. In general, the lower lip seems to overlap the teeth more than the upper lip. Hence, it is impossible to form many of the speech sounds. If the accelerometer were imbedded in the veneer, this problem would not exist. Hence, the lower jaw mounting has been abandoned until we are able to embed the accelerometer into the veneer.

3.1.9 Tooth Microphone Comfort Study

The purpose of this study was primarily to determine whether the tooth veneer could be worn for 40 hours with no discomfort. Also determined was the degree of speech impairment, possible diet restrictions, and the cosmetic demerits of this prosthetic device.

Three subjects, MG, JCO and JPC, took part in the study. Each wore a custom fitted device. The subjects were instructed to wear the device 40 hours continuously without removal. This would, of course, include the working day, while eating and sleeping.

Results:

The tooth microphone caused no discomfort whatsoever during the 40-hr. period. After a short time one becomes accustomed to any feeling present and soon forgets the veneer is worn. All subjects expressed the opinion that the veneer could be worn indefinitely with no discomfort whatsoever. Dentists report that some individuals leave bridges and/or plates in their mouths for periods as long as a year. Hence, there is no reason to doubt that a properly fitted veneer could be worn for long periods.

Subject MG wore the accelerometer for two 40-hr. periods (not consecutive). During the first time he did not wear the dummy accelerometer, while during the second period he did. He found no difference in the comfort of these two tests. Subjects JCO and JPC wore the veneer without the accelerometer. Since we expect to encapsulate the seismic element into the veneer with no protrusion through the lips with the exception of a tiny lead which may also be eliminated through electromagnetic coupling, we felt justified in neglecting the dummy unit.

Subject MG drank liquids such as soup, coffee and water, for the first 20 hours. Later he found that he could also eat foods such as hot dogs, tomatoes,

A3-4

lettuce, and other soft foods. The tooth veneer did not react unfavorably with hot coffee or cold water.

Subject JPC was able to eat coffee cake and sandwiches which required biting with the front teeth.

Hence, one can summarize that a diet of liquid and soft foods presents no problem to a person wearing a tooth veneer.

Speech was not impaired on any of the three subjects.

The sight of the tooth veneer, of course, caused some comment. If teeth were painted on the veneer and the accelerometer encased in the material, it would hardly be noticed.

Summary:
The tooth microphone has been worn by three individuals for 40 hours continuously. The device is hardly noticed and could be worn indefinitely with no comfort problem, in the opinions of the subjects. Liquids and soft foods may be easily eaten and the device does not affect speech.

3.1.10 Adaptation of Tooth Microphone to AIC-10 System

The accelerometer used with the tooth veneer is a piezoelectric device; hence it has a very low capacity of 80 uuf and a very high internal impedance at audio frequencies. The input impedance of the AIC-10 microphone input is only 5 ohms in order to match the low impedance dynamic microphones used with this equipment. Hence, the main function of an amplifier to adapt the tooth microphone is impedance translation. An amplifier was designed which presents a relatively high input impedance to the tooth accelerometer, and a low impedance transformer output of about 3 ohms. The circuit diagram is shown in Figure 13, and the frequency response in Figure 14. The tooth microphone used with the adaptor will deliver approximately the same voltage at the same impedance as the AIC-10 microphones with the same speech input.
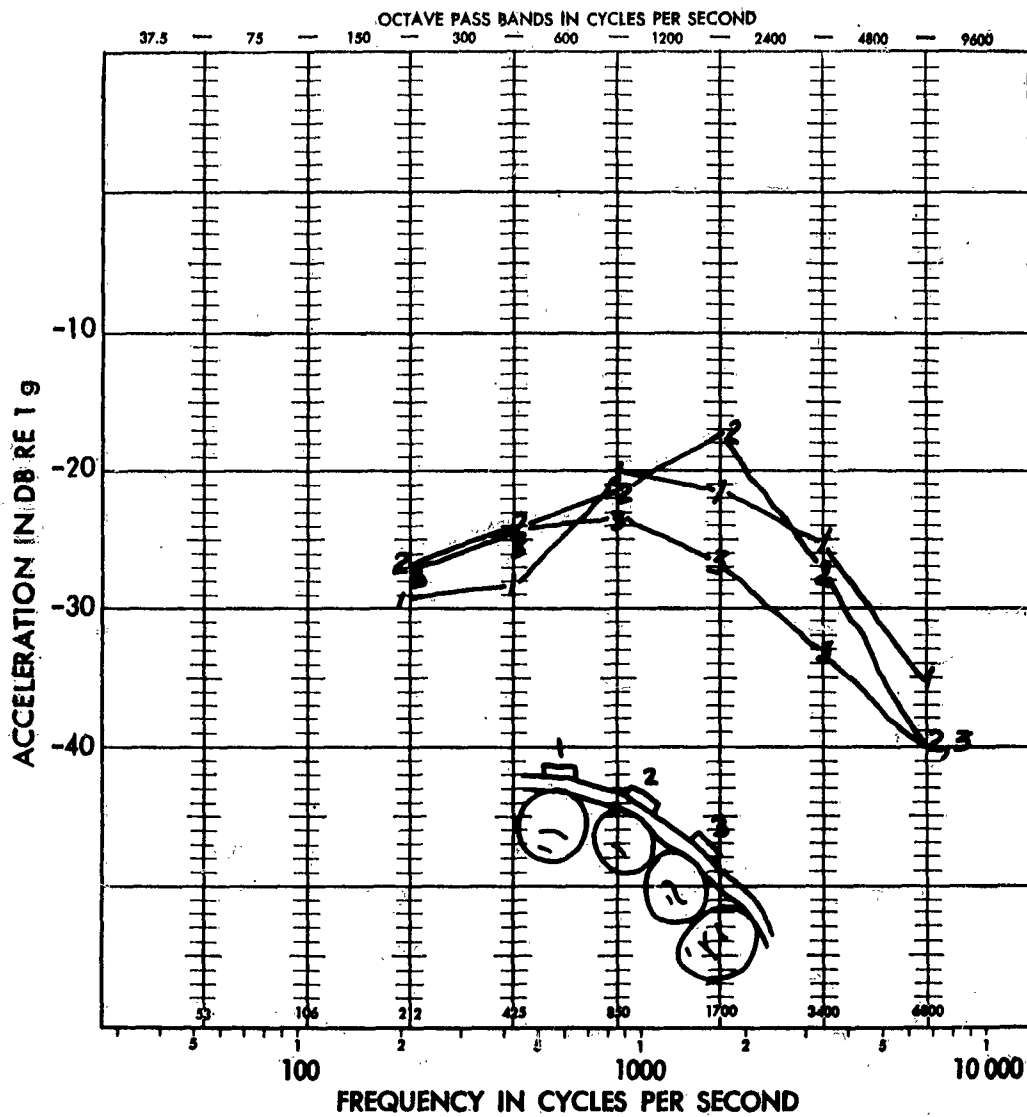
TOOTH VENEER

Figure A3.1-1

TOOTH VENEER

Figure A3.1-2
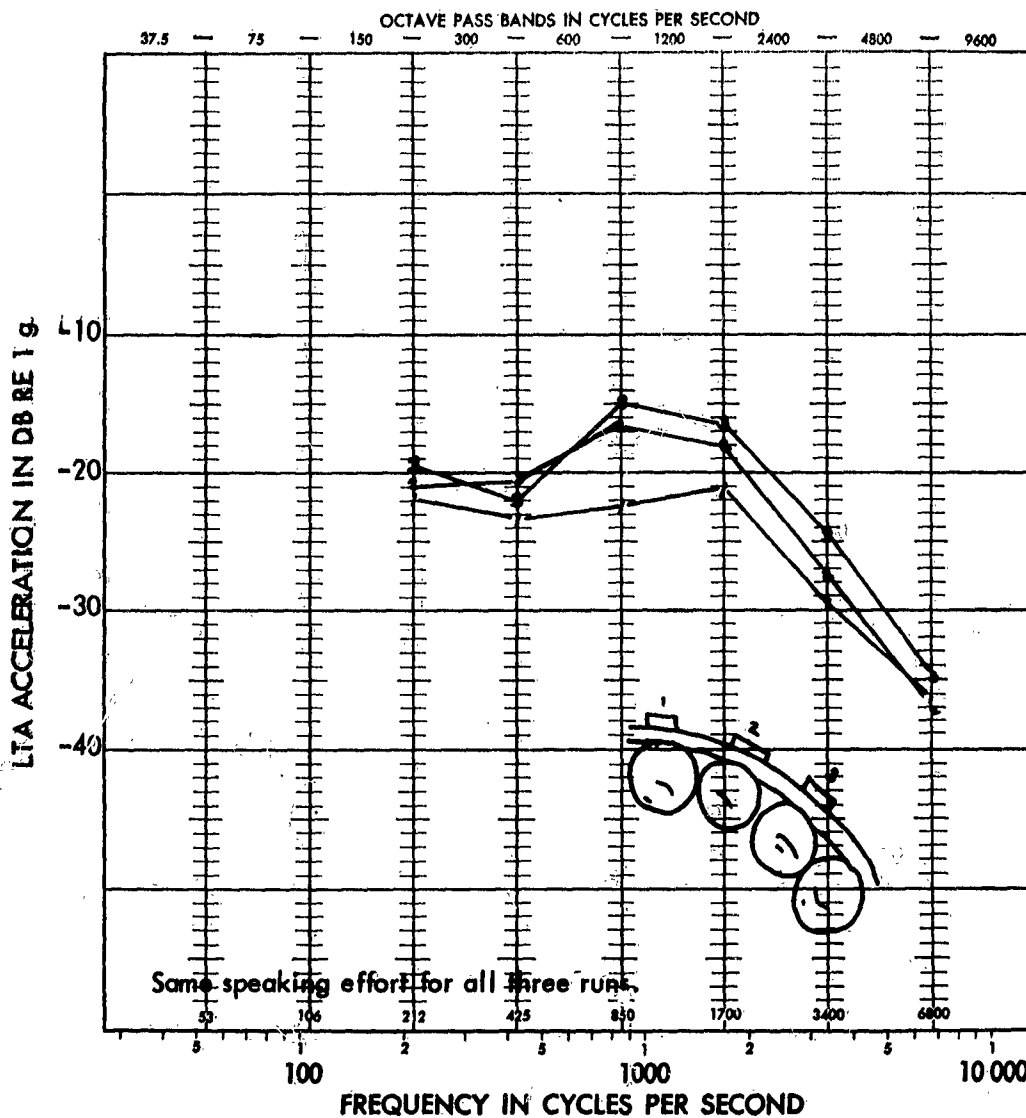
TOOTH VENEER

Figure A3.2-3

EFFECT OF ACCELEROMETER POSITION ON
TOOTH VENEER ON SPEECH PICKUP
Subject: JPC

Curve 1: Tooth Veneer - Position #1
  2:    "   "   -   "   #2
  3:    "   "   -   "   #3

Figure A3.1 - 4

37.5 — 75 — 150 — 300 — 600 — 1200 — 2400 — 4800 — 9600

Same speaking effort for all three runs.

FREQUENCY IN CYCLES PER SECOND

LTA ACCELERATION IN DB RE 1 g.

EFFECT OF ACCELEROMETER POSITION ON
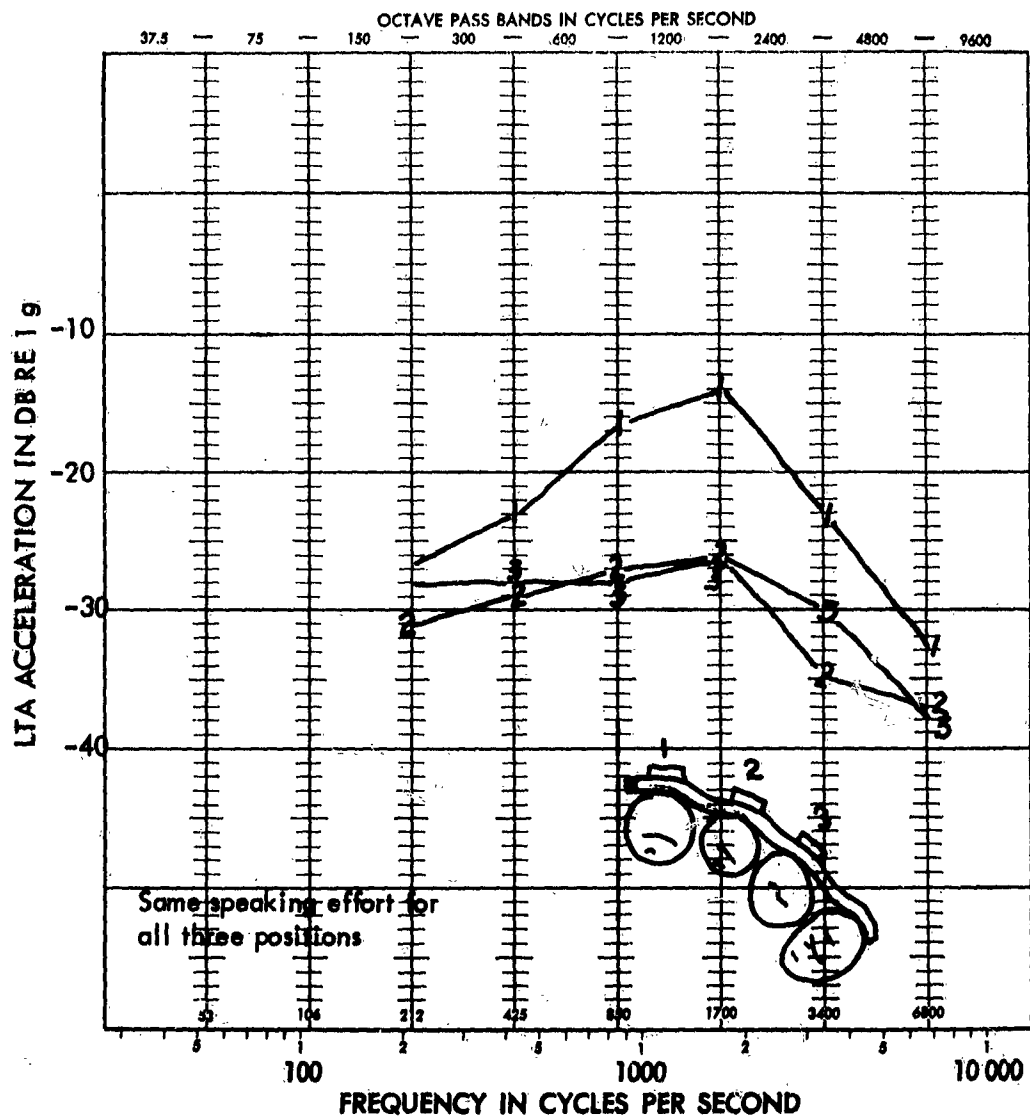TOOTH VENEER ON SPEECH PICKUP
Subject: MG

Curve 1: Tooth Veneer – Position #1 (over left upper
central incisor)

2: "   "   –   "   #2

3: "   "   –   "   #3

Figure : A3.1 – 5

OCTAVE PASS BANDS IN CYCLES PER SECOND

37.5 — 75 — 150 — 300 — 600 — 1200 — 2400 — 4800 — 9600

LTA ACCELERATION IN DB RE 1 g

Same speaking effort for
all three positions
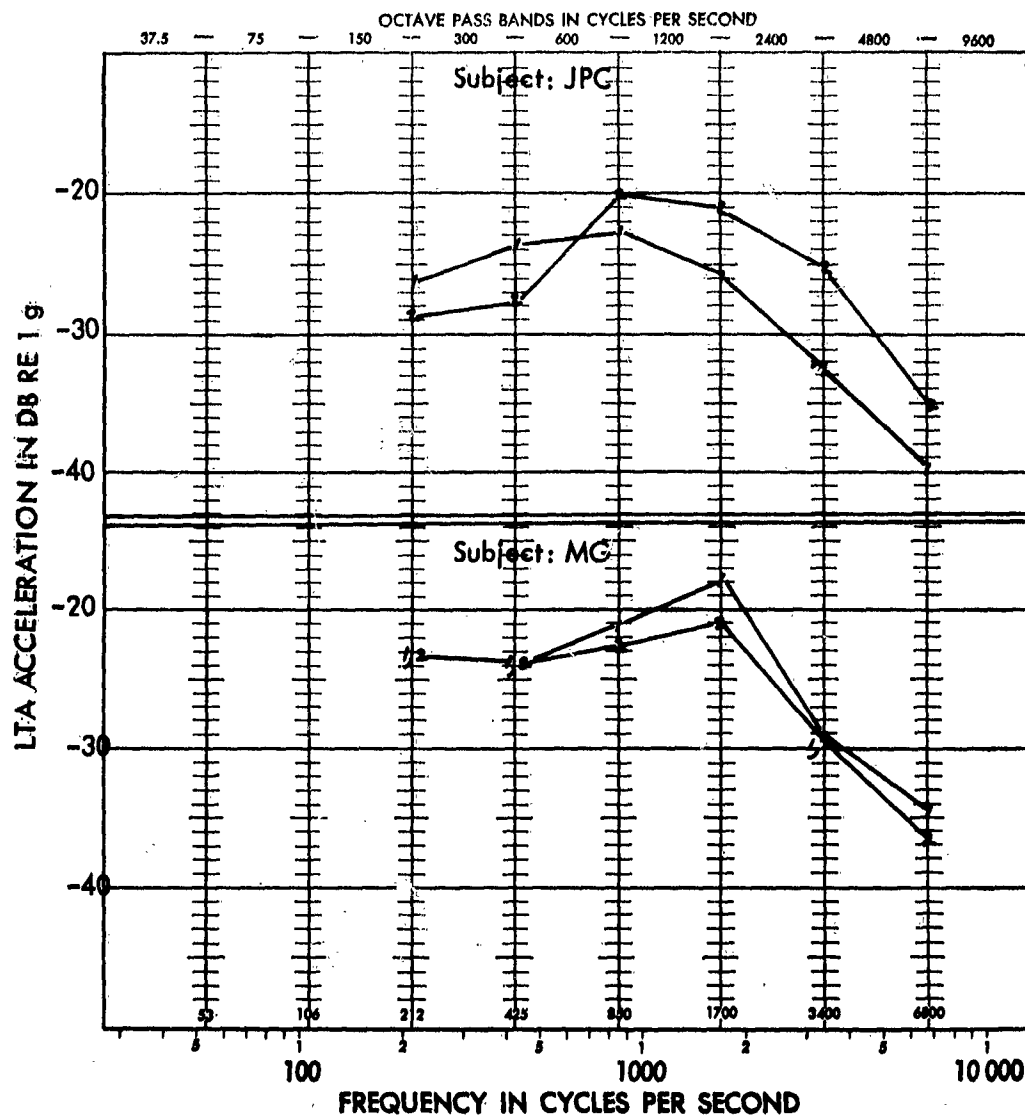
FREQUENCY IN CYCLES PER SECOND

EFFECT OF ACCELEROMETER POSITION ON
TOOTH VENEER ON SPEECH PICKUP
Subject: JCO

Curve 1: Tooth Veneer – Position #1 (over left upper central incisor)
2:   "   "   –   "   #2
3:   "   "   –   "   #3

Figure   A3.1 – 6

COMPARISON OF SPEECH OUTPUT FROM TOOTH
BAND AND TOOTH VENEER FOR SAME SPEAKING EFFORT

Curve 1: Accelerometer mounted on tooth band on left upper
   central incisor
2: Accelerometer mounted on tooth veneer. Position #1
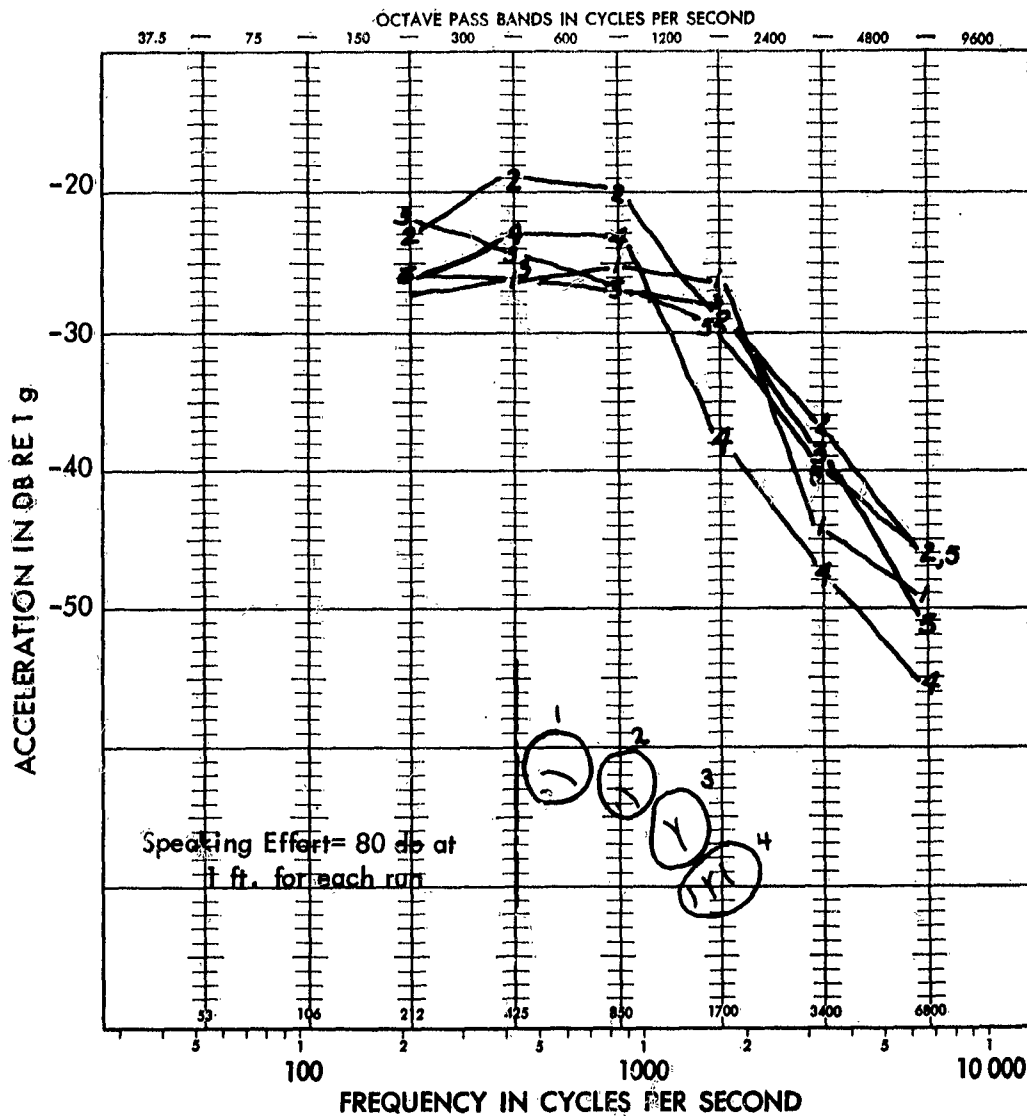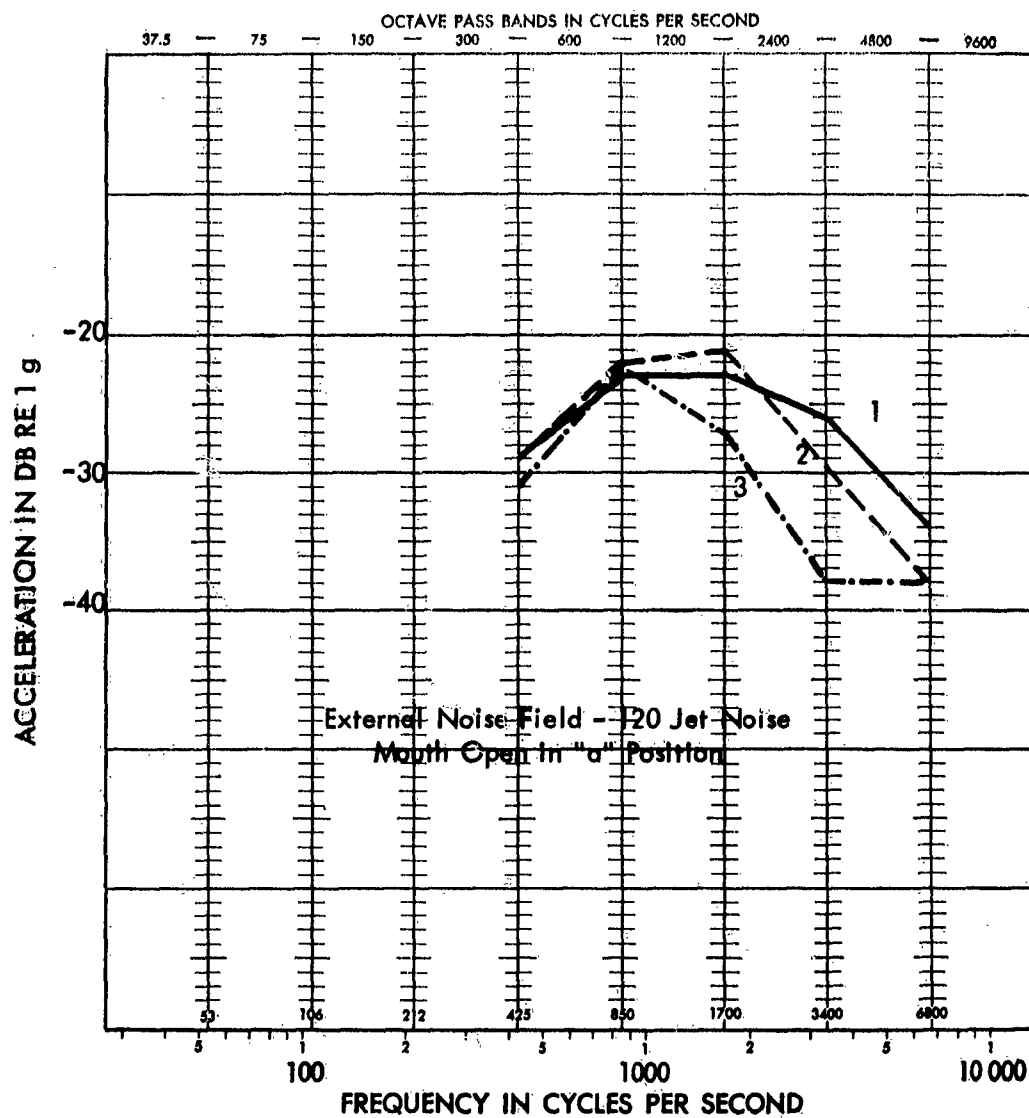   over left upper central incisor

Figure A3.1 - 7

Figure 8

Figure A3.1 - 9

SPEECH OUTPUT AS MEASURED BY ACCELEROMETER.
TOOTH BANDS MOUNTED ON SEVERAL TEETH
Subject: MG

Curve 1: Position #1 (upper jaw)(left upper central incisor)
2:    "   #2   "
3:    "   #3   "
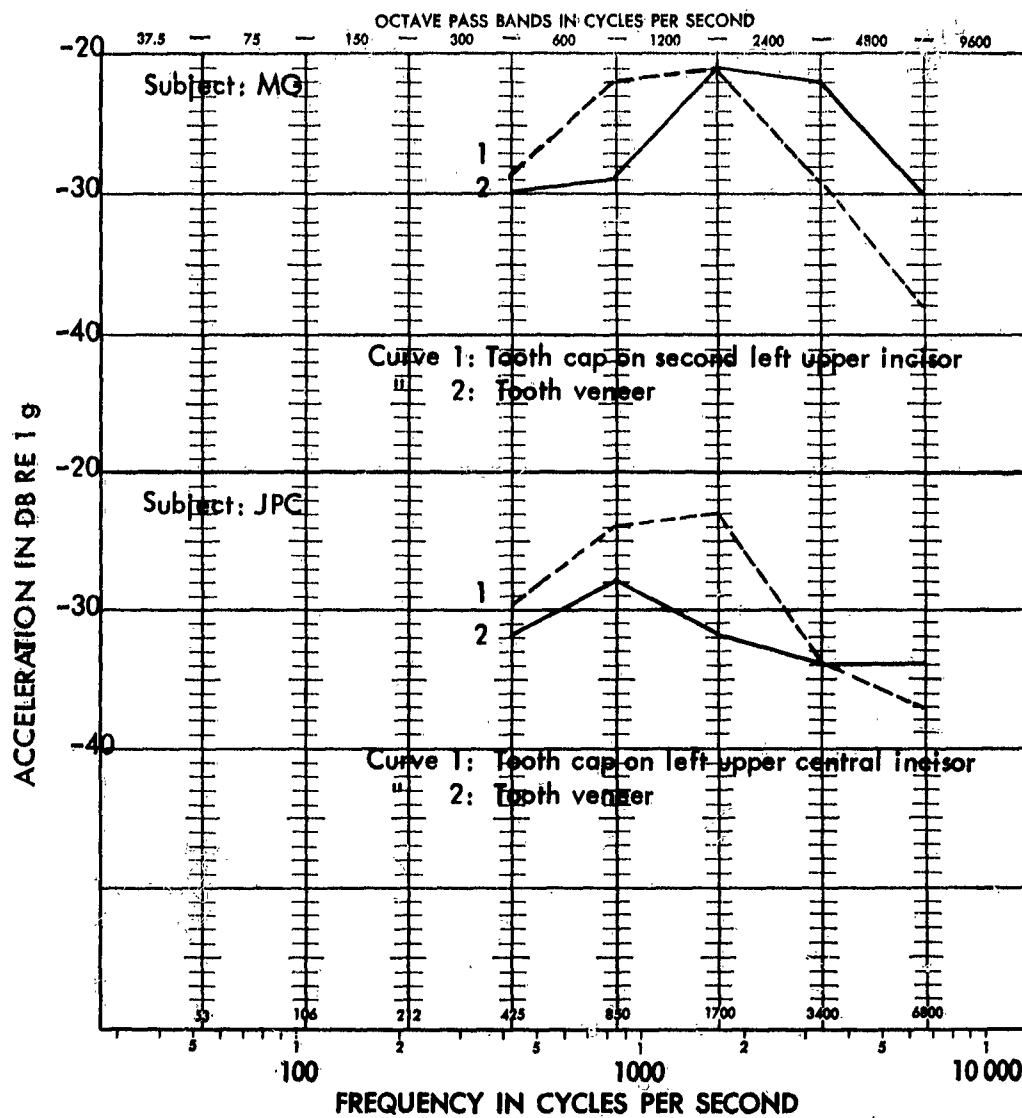4:   "   #4   "
5:    "   #1 (lower jaw)

Figure A3.1 - 10

OCTAVE PASS BANDS IN CYCLES PER SECOND

OUTPUT OF ACCELEROMETER AS MOUNTED
ON SEVERAL TEETH IN NOISE
Subject: MG

Curve 1: Tooth band mounted on left upper central incisor
2: Tooth band mounted on second left upper incisor
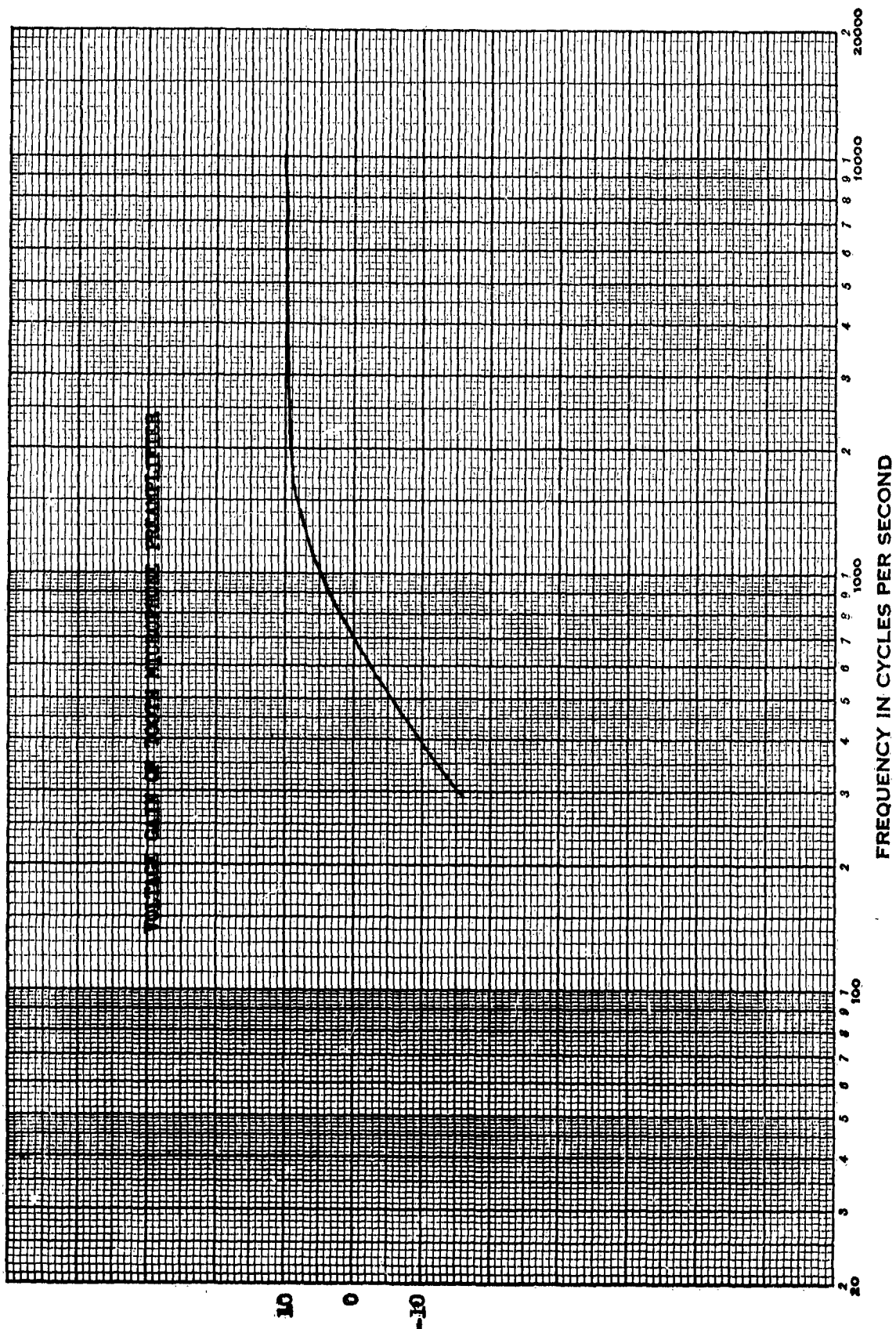3: Tooth band mounted on left lower central incisor

Figure A3.1 -11

OCTAVE PASS BANDS IN CYCLES PER SECOND

Subject: MG

Curve 1: Tooth cap on second left upper incisor
      "   2: Tooth veneer

ACCELERATION IN DB RE 1 g

Subject: JPC

Curve 1: Tooth cap on left upper central incisor
      "   2: Tooth veneer

FREQUENCY IN CYCLES PER SECOND

EXTERNAL NOISE =120 DB

MOUTH OPEN IN "A" POSITION

Figure A3.1 - 12

VOLTAGE GAIN OF TOUGH MICROPHONE PREAMPLIFIER

FREQUENCY IN CYCLES PER SECOND

Voltage Gain in Decibels

Figure A3.1 - 13

TOOTH MICROPHONE PREAMPLIFIER
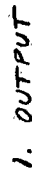
Figure A3.1 - 14

3.2 FOREHEAD MICROPHONE

3.2.1 SUMMARY

This report describes progress made in the development of a forehead microphone. The work was sponsored by North American Aviation, Inc., Human Factors Section.

Preliminary work done at this Laboratory under Contract AF33(616)-3710 indicated that a completely exposed forehead microphone of simple design would yield an 80% PB word intelligibility in a jet noise field of 110 db overall and a Speech Interference Level of 95 db. Estimates of the anticipated noise levels in the crew position of advanced North American Aviation aircraft indicate that the forehead microphone may be practical as an alternative to the AIC-10. The forehead location possesses several attractive advantages, particularly improved comfort prospect and freedom from degradation of performance due to mispositioning.

Measurements were made to determine the effect of the following parameters on the operation of a forehead microphone in noise:

(1) Microphone Type – diaphragm vs. inertial
(2) Contact pressure
(3) Forehead Position
(4) Material between microphone and forehead

The results of these measurements are that (1) an inertial type transducer affords 10 db greater signal-to-noise ratio (S/N) over a diaphragm contact or air cavity transducer, (2) increasing the contact static pressure over 0.3 psi does not improve the S/N. A minimum of 0.2 psi is required. (3) The microphone can be mounted within an imaginary rectangle 1 in. high and 3 in. wide centered on the center of the forehead without appreciable change in performance. (4) A thin headband between the transducer and the forehead will not decrease the S/N.

Progress was made in adapting two existing commercial units, the Sonotone 0-1 and the Military MC-253B to the AIC-10 system. A small transistor amplifier-equalizer packaged in a 1 cu. in. box was constructed which permits these microphones to be used in place of the AIC-10 microphones. Further development will be necessary when a final forehead microphone design is completed.

Future work would include (1) basic transducer design in order to attain the maximum S/N, (2) miniturization of the transducer based on this design – the design goal should be 1/2 in. in diameter, 1/4 in. thick, (3) final adaptation to the AIC-10 system for complete interchangability with the AIC-10 microphones, (4) comfort studies, (5) system articulation tests.

3.2.2 INTRODUCTION TO THE FOREHEAD MICROPHONE

When the vocal mechanism is excited, vibrations are transmitted throughout the entire body. Intelligible speech may be detected in many areas. However, the forehead and tooth positions appear, on the basis of measurement and listening tests, to be best.

The results from a series of articulation tests using the MC-253B magnetic microphone with diaphragm in contact with the forehead is shown in Figure 1. Notice that the ordinate is speaking effort. The speaking effort should be limited to raised speaking efforts. The results show that for a raised speaking effort the forehead microphone will yield an 80% PB word score in a SIL of 95 db. In a helmet completely enclosing the head the noise may be increased to an SIL of 105 db. The SIL (speech interference level) is the average of the sound pressure levels in the 600-1200, 1200-2400 and 2400-4800 octave bands. The noise spectrum in which these microphones were tested is shown in Figure 2. It is approximately 5 db higher than the maximum jet spectrum envelope.

The forehead microphone, although clearly not as usable in as high a noise environment as the AIC-10 equipment, has a probable advantage in wearability. Since its position is fixed, it is not as subject to degradation of performance due to mis-positioning as in the case with noise-cancelling lip microphones.

3.2.3 STUDY OF PARAMETERS AFFECTING SIGNAL-TO-NOISE RATIO
OF THE FOREHEAD MICROPHONE

Microphone Type

Two commercial units were chosen for the studies because they were readily available. Neither was designed to be used on the forehead; hence they do not represent the ultimate of development. The two transducers are the MC-253B, a World War II production microphone, and the Sonotone 0-1 Bone Oscillator, which is used as a receiver unit in bone conduction hearing aids.

The MC253B is a conventional magnetic microphone. Its dimensions and a schematic diagram are shown in Figure 3a. The diaphragm may be placed directly on the forehead, and as long as the pressure is not excessive the magnetic circuit is not affected.

Applied Pressure

A study was made to determine the effect of applied pressure on the performance of the forehead microphone. For adequate comfort a pressure of 10 mm hg, .19 psi, has been set as a design goal by helmet manufacturers. The applied pressure should never exceed the pressure in the capillaries, which is known to be from 18 to 30 mm or from .35 to .59 psi.

The S/N for the two microphones described above was measured as a function of applied pressure. Measurements were made at a fixed speaking effort and in a constant noise field of 120 db. The apparatus used to control the static pressure did not affect the results. The results are shown in Figures 7 and 8 for one subject; similar results were recorded for another subject.

One may conclude that an applied pressure exceeding .3 lbs/in.^{2} does not significantly improve the S/N. An applied pressure of .2 psi would appear to be adequate for either transducer.

Forehead Mounting Location

Measurements were performed to determine the effect of forehead mounting location on the performance of the forehead microphone in noise. The results indicate that the central mounting position, at a distance of 1 1/2 in. to either side of the center of the forehead, yield about the same S/N ratio.

Band Between Microphone and Forehead

It may be desirable to mount the forehead microphone in a headband which fits between the forehead and the microphone. A short test was run to determine whether such a band will affect the S/N. The material tested was .045 in. thick which is considerably thicker than necessary to support the microphone. The decrease in S/N when using the band is shown in Figure 9, for two subjects using the Sonotone 0-1 oscillator only. There is no decrease except in the 2400-4800 octave band. For thinner materials, no significant decrease should result.

3.2.4 ADAPTATION OF FOREHEAD MICROPHONE TO THE AIC-10 SYSTEM

The problem of adapting the Sonotone or MC-253B forehead microphones to the AIC-10 system is threefold: (1) to supply sufficient electrical gain so that the forehead microphone will drive the system to full output; (2) to provide equalization so as to boost the high frequency output of the forehead microphone; (3) impedance matching.

The open circuit output voltage of the forehead and M-32/AIC microphones is approximately equal. However, the impedance of the forehead microphones is 1000 ohms inductive at 1 KC to 5 ohms for the AIC-10 microphones. The AIC-10 amplifiers incorporate

The Sonotone O-1 is an inertial type and is shown in Figure 3b. The case is one piece. However, if the case is displaced there is relative motion between the case and the mass inside. This changes the magnetic circuit and a current is produced. This transducer was designed to be used on the mastoid; however, the mechanical impedance of the mastoid and forehead are nearly the same.

The open circuit output voltage of these microphones on the forehead with an applied pressure of 0.3 lbs/in.^{2} is shown in Figure 4. For comparison the response of the M-32/AIC in an A-13A oxygen mask is also shown. These curves represent long-time average voltage readings, i.e. they are read on a voltmeter with a very long time constant. The peak voltage corresponding to speech peaks will be approximately 18 db higher in all bands. To correct the voltages for other speaking efforts the following corrections should be applied: (1) subtract 18 db for normal conversational level; (2) subtract 9 db for raised speaking level.

Comparison was made of the performance of the MC-253B and the Sonotone O-1 microphones in noise. A fixed speaking effort - "raised" - and 120 db noise field were used. Results are shown in Figures 5 and 6 for two subjects. The Sonotone affords 8 - 13 db on the average higher S/N than the MC-253B.

The qualitative explanation of this difference in S/N may be as follows: Suppose both microphones were placed in a uniform acoustic field at a frequency such that the wavelength is larger than the dimensions of the transducer cases. The Sonotone should show no output, since the same pressure will exist on all six faces; therefore, there will be no relative motion between the case and the seismic mass. However, the MC-253B will have an output because the diaphragm is exposed. Now suppose that when the microphones are on the forehead, some of the external noise field propogates through the skin between the skull and microphone. When this reaches the microphone face, if it were nearly in phase and of the same amplitude as the external field striking the exposed microphone faces, the inertial type Sonotone should read no output, in contrast to the diaphragm type MC-253B.

The prediction of the noise field in which the forehead microphone will perform as shown in Figure 1 was based on a diaphragm type transducer having the same characteristics as the MC-253B. Hence there is good promise that an inertial type will be usable in high noise fields. However, articulation tests would be needed to substantiate this.

A3-9

an input transformer with a primary impedance of 5 ohms and a high secondary impedance which provides an effective voltage gain. Hence, the relatively high impedance forehead microphone cannot be interchanged with the AIC-10 microphones without additional gain.

A miniature preamplifier-equalizer was designed for use with either the Sonotone 0-1 or MC-253B. The circuit is shown in Figure 10. The entire circuit, including a 1.4 v mercury cell with a capacity of 1000 hours was packaged in a box 1 x 1 x 1 in. The electrical gain (excluding the transformer) is shown in Figure 11. The transformer was needed to prevent loading of the final transistor stage. The output impedance is 4 ohms.

It is estimated that if the 1.4 v DC can be supplied from the AIC-10 system, then the entire preamplifier-equalizer could be built into a plug connector similar to the U-94/J.

It should be stressed that this design is a preliminary one. It was constructed primarily for demonstration purposes. Until the final microphone design is settled, further electronic development is unwarranted.

3.2.5 FUTURE DEVELOPMENT

Development of an inertial forehead microphone 1/2 in. in diameter and 1/4 in. thick appears practical using miniature transducers as the seismic element. The microphone should be designed to provide maximum signal-to-noise ratio. The output, response, and impedance should be controlled so that no electronic treatment is necessary, if possible.

Some design will be necessary in building the forehead microphone into a helmet. The microphone must be isolated from large surface areas for the S/N to remain high.

After the microphone is mounted properly in the helmet, articulation tests should be made to determine the capability of the entire system in noise.

Comfort study tests should be made on the microphone/helmet combination.
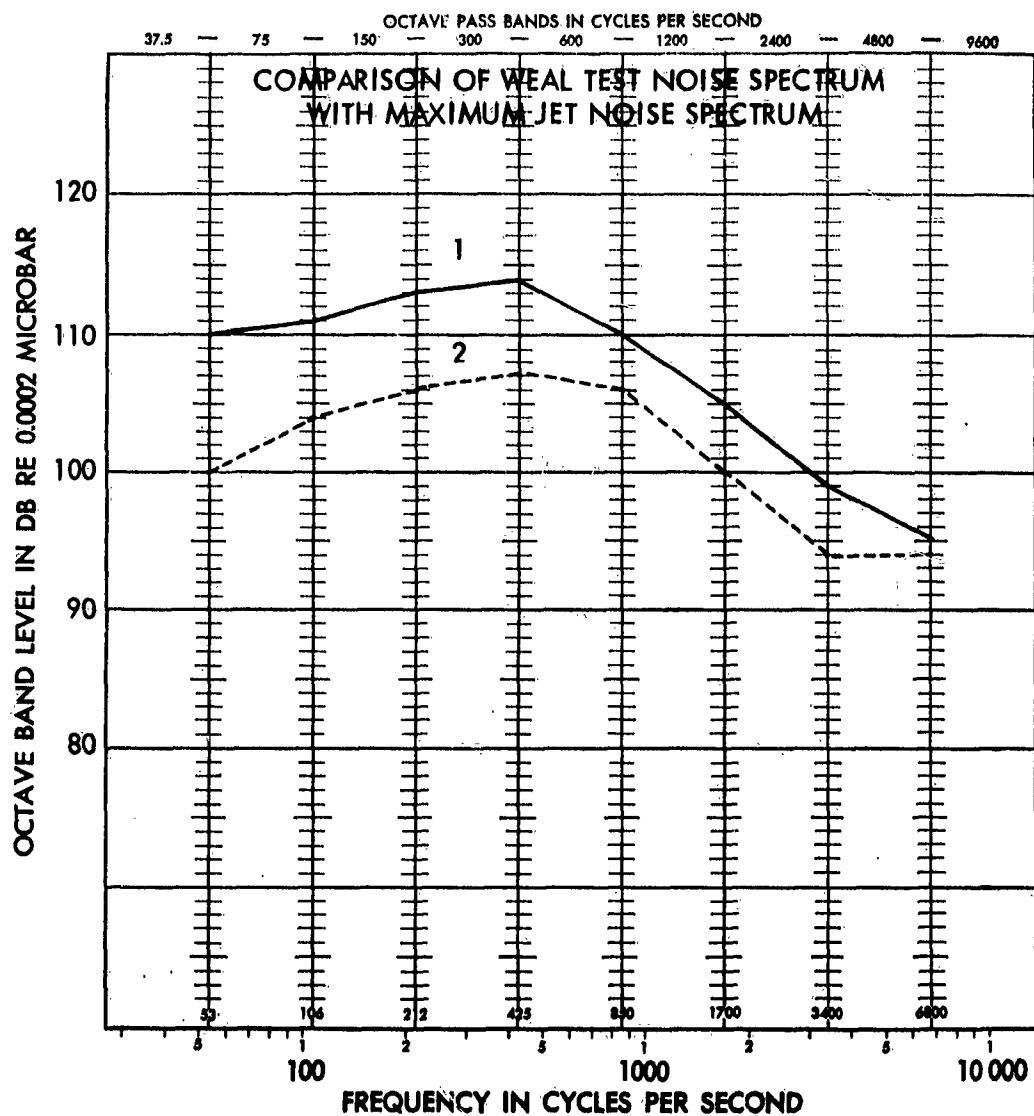
SPEAKING EFFORT REQUIRED TO ACHIEVE
AN 80% PB ARTICULATION SCORE AS A
FUNCTION OF THE SPEECH INTERFERENCE
LEVEL OF THE MASKING NOISE

Figure 1
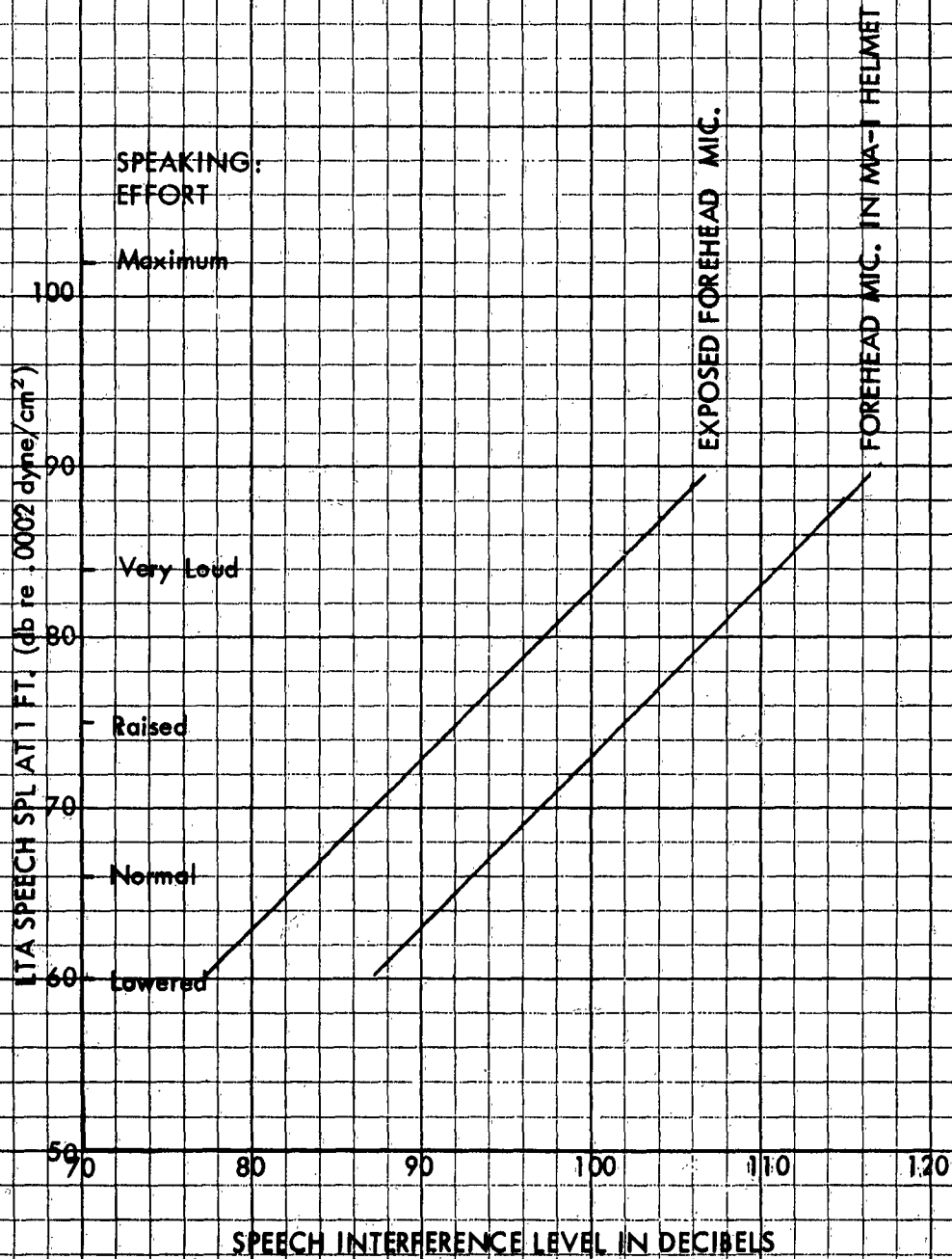
Note: The masking noise spectrum is shown in Figure 2. The overall level is 15 db higher than the SIL.
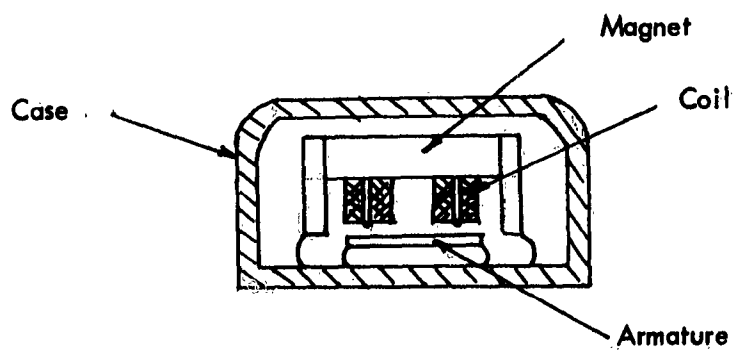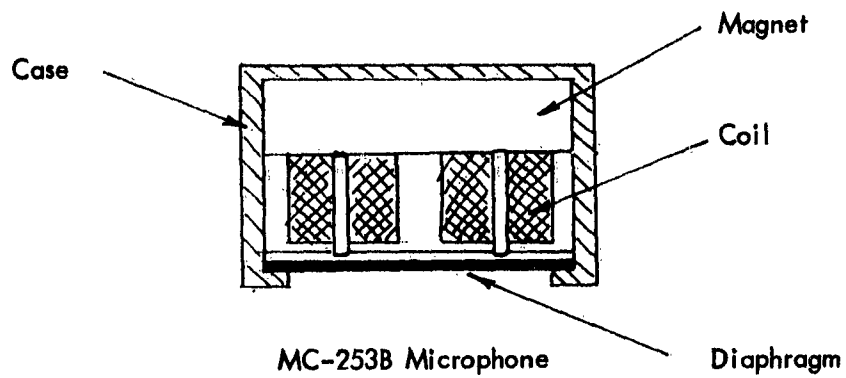
Figure A3.2 - 1

OCTAVE PASS BANDS IN CYCLES PER SECOND

37.5 — 75 — 150 — 300 — 600 — 1200 — 2400 — 4800 — 9600

COMPARISON OF WEAL TEST NOISE SPECTRUM
WITH MAXIMUM JET NOISE SPECTRUM

FREQUENCY IN CYCLES PER SECOND

OCTAVE BAND LEVEL IN DB RE 0.0002 MICROBAR

Curve 1: WEAL 120 db Test Spectrum

2: Maximum Noise Level (excluding auxiliary equipment) jet
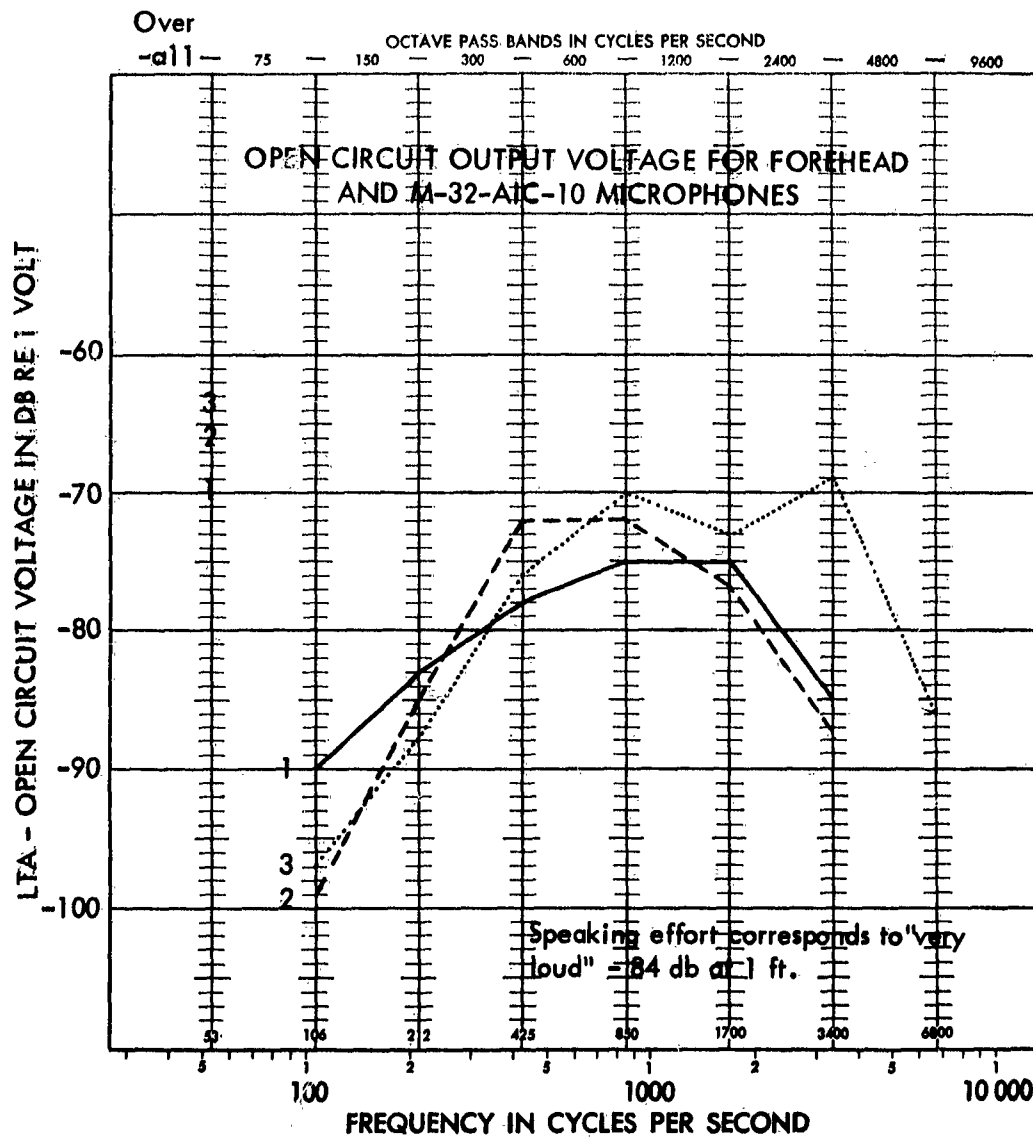   aircraft in level flight – crew position. (WADC TN 56–411)

Figure A3.3 – 2

Case

Magnet

Coil

MC-253B Microphone

Diaphragm

Magnet

Case

Coil

Armature

Sonotone 0-1 Bone Oscillator

Figure A3.2 - 3

Figure showing open circuit output voltage curves:

OPEN CIRCUIT OUTPUT VOLTAGE FOR FOREHEAD AND M-32-AIC-10 MICROPHONES

Over-all — 75 — 150 — 300 — 600 — 1200 — 2400 — 4800 — 9600

Y-axis: LTA - OPEN CIRCUIT VOLTAGE IN DB RE 1 VOLT (-60, -70, -80, -90, -100)

X-axis: FREQUENCY IN CYCLES PER SECOND (100, 1000, 10 000)

Speaking effort corresponds to "very loud" = 84 db at 1 ft.

Curve 1: MC-253B
      2: Sonotone 0-1
      3: M-32/AIC in oxygen mask

Note: Speaking effort for above curves is 9 db above raised effort and 18 db above normal effort
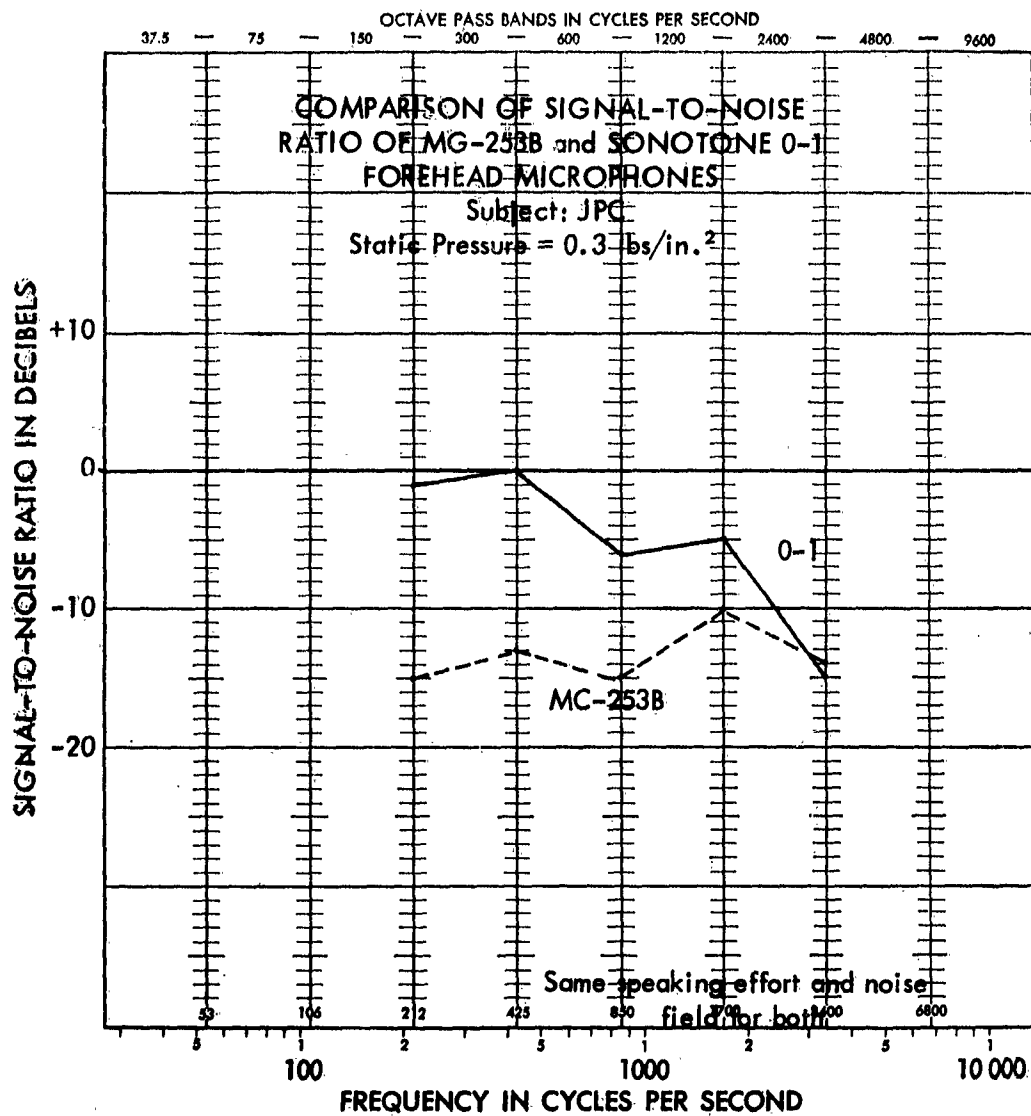
Figure A3.2 - 4

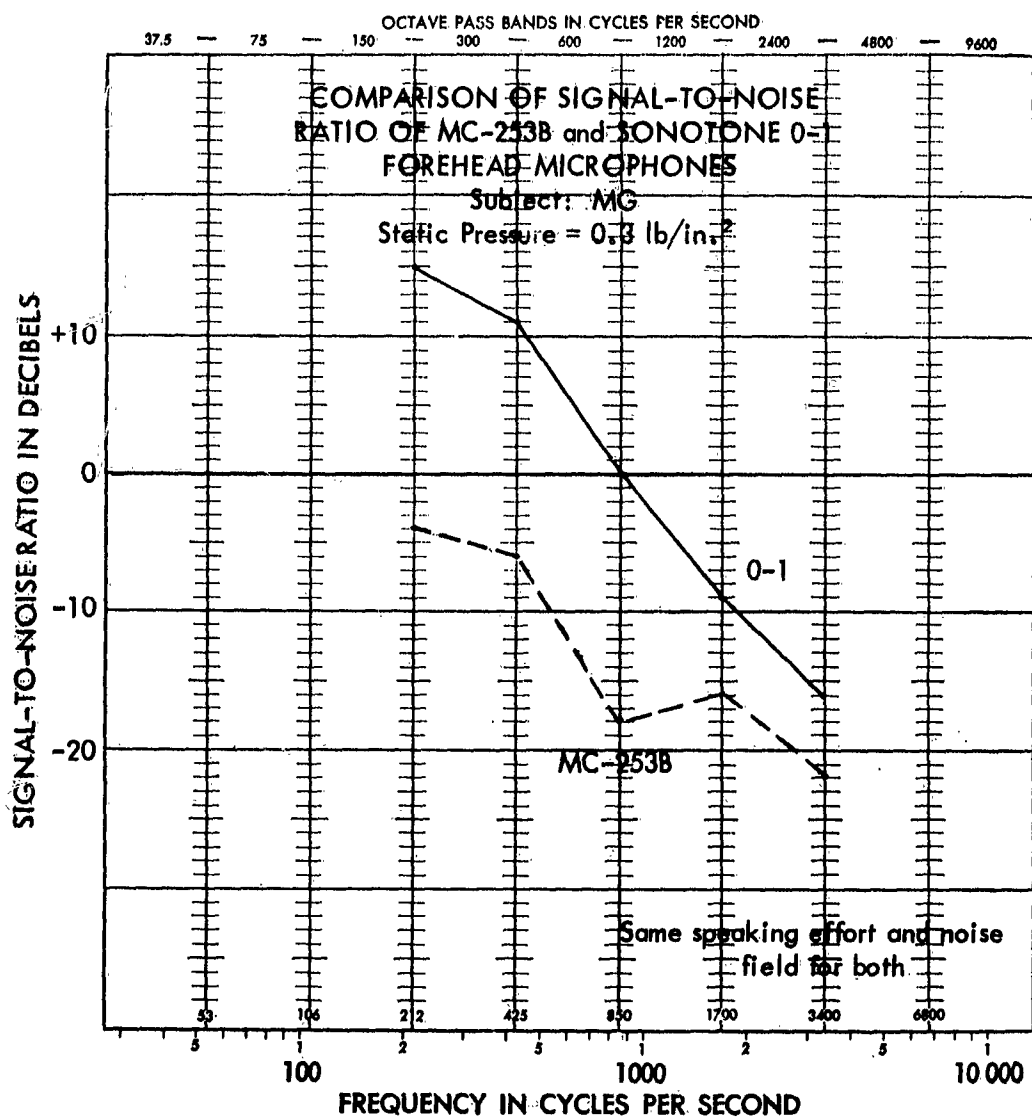OCTAVE PASS BANDS IN CYCLES PER SECOND

COMPARISON OF SIGNAL-TO-NOISE
RATIO OF MG-253B and SONOTONE 0-1
FOREHEAD MICROPHONES
Subject: JPC
Static Pressure = 0.3 lbs/in.²

SIGNAL-TO-NOISE RATIO IN DECIBELS

0-1

MC-253B

Same speaking effort and noise
field for both

FREQUENCY IN CYCLES PER SECOND

Figure A3.2 - 5

COMPARISON OF SIGNAL-TO-NOISE RATIO OF MC-253B and SONOTONE 0-1 FOREHEAD MICROPHONES
Subject: MG
Static Pressure = 0.3 lb/in.²

Figure A3.2 – 6

EFFECT OF FOREHEAD CONTACT PRESSURE ON SIGNAL-TO-NOISE RATIO

Subject - MG; MC-253B Microphone
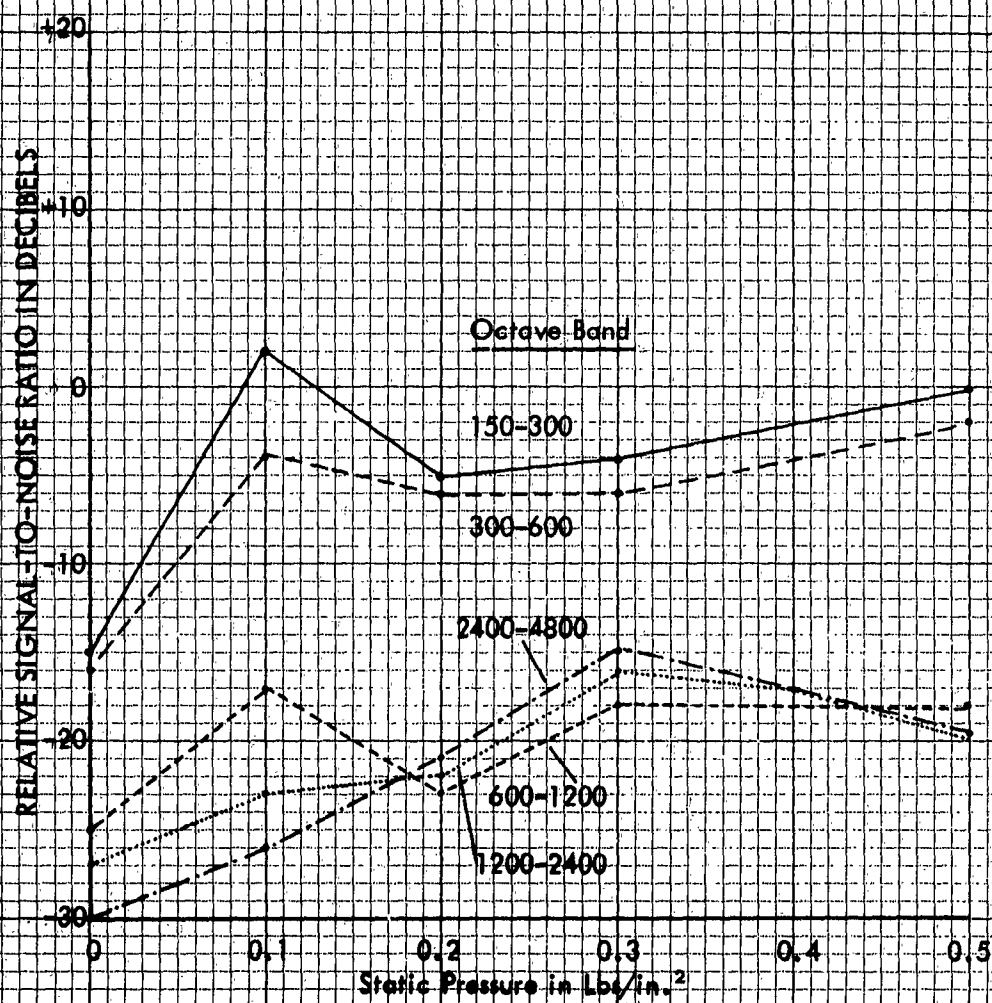
Figure A3.2 - 7

EFFECT OF FOREHEAD CONTACT PRESSURE
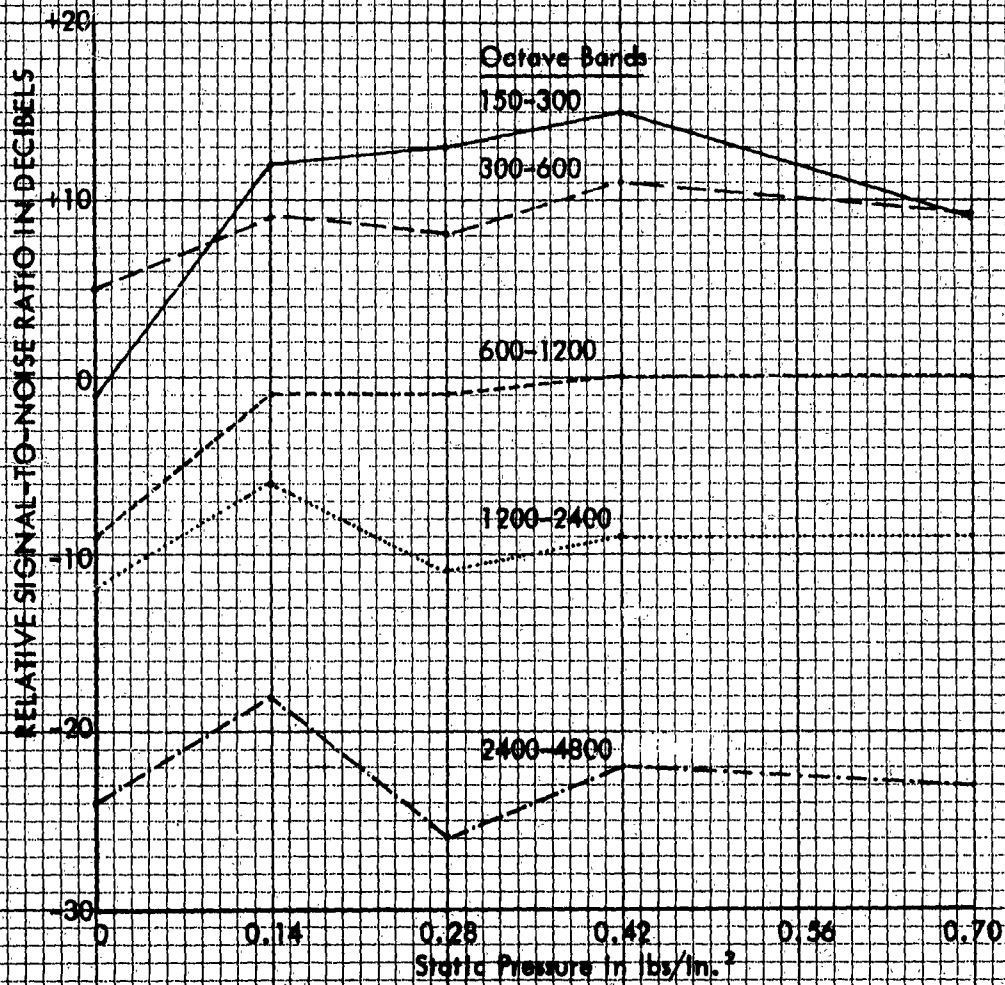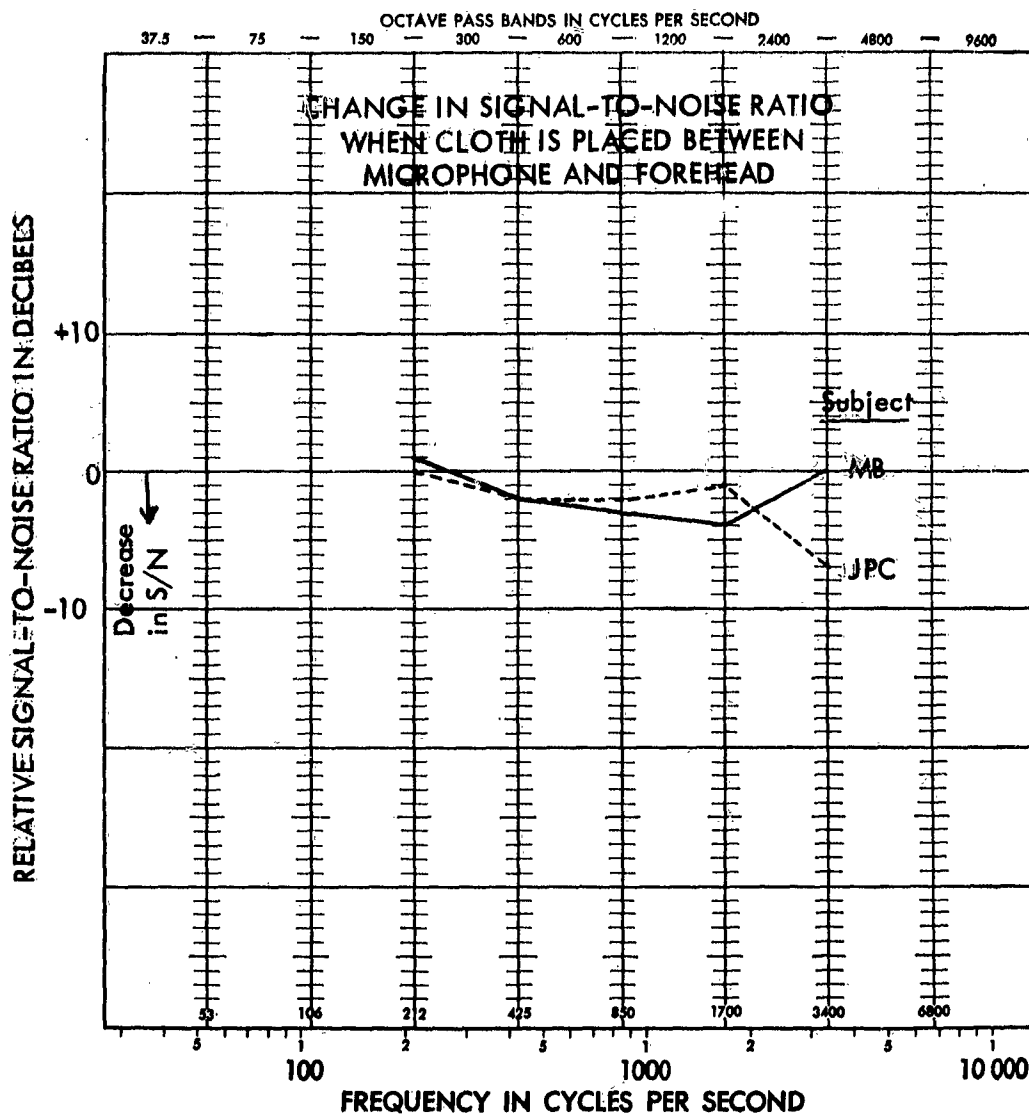ON SIGNAL-TO-NOISE RATIO

Subject: MG; Sonotone 0-1 Bone Oscillator

Figure A3.2 - 8

OCTAVE PASS BANDS IN CYCLES PER SECOND

CHANGE IN SIGNAL-TO-NOISE RATIO
WHEN CLOTH IS PLACED BETWEEN
MICROPHONE AND FOREHEAD

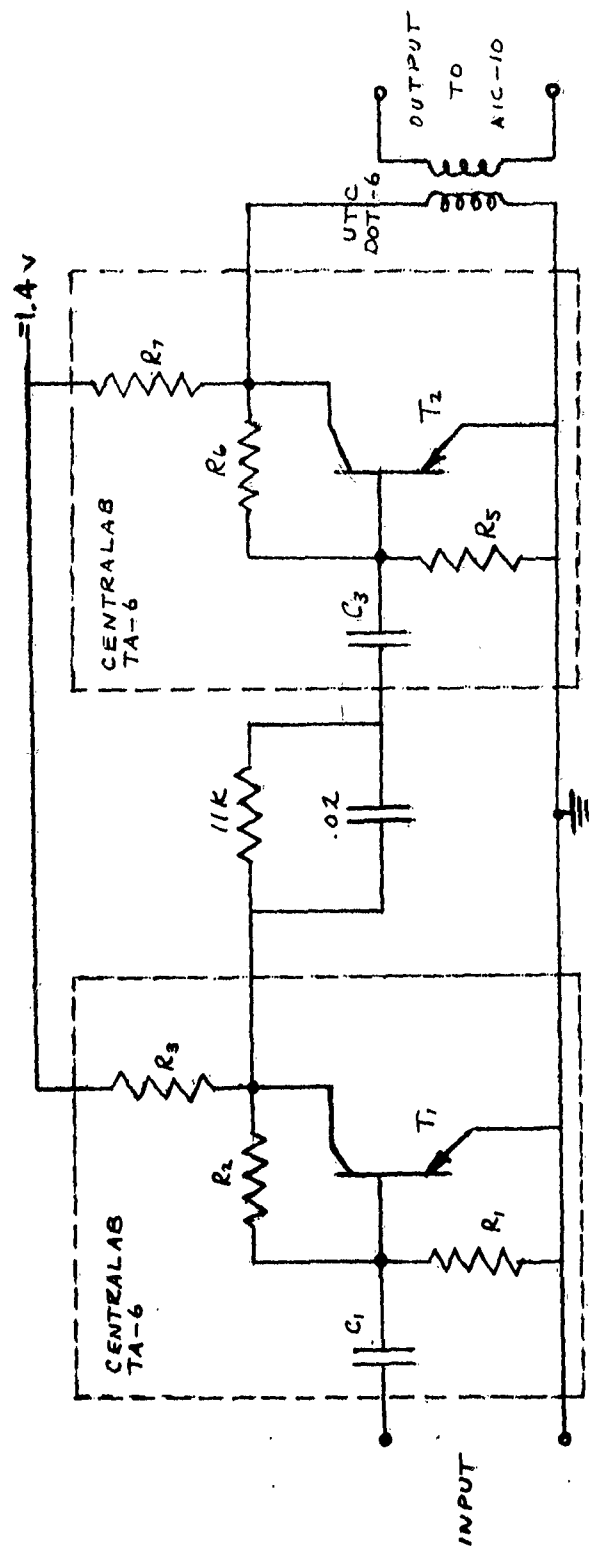RELATIVE SIGNAL-TO-NOISE RATIO IN DECIBELS

Decrease in S/N

FREQUENCY IN CYCLES PER SECOND

Note: 1. Sonotone 0-1 Bone Oscillator
       2. Cloth, .045 in. thick

Figure A3.2 - 9

N.A.A. FOREHEAD MICROPHONE PREAMPLIFIER

NOTE: COMPONENT VALUES IN
CENTRALAB TA-6 PACKAGED
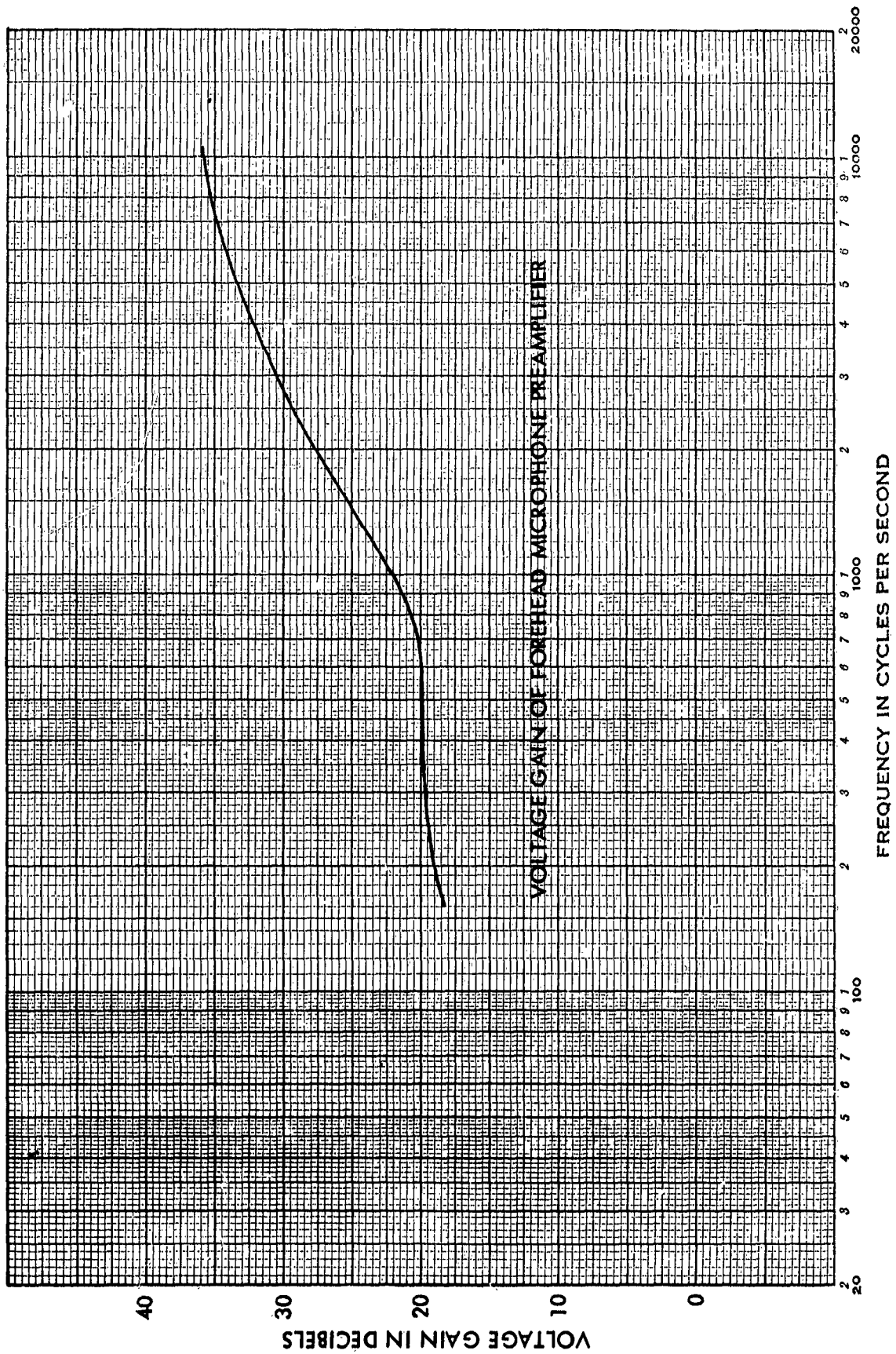TRANSISTOR AMPLIFIERS ARE
NOT STATED BY MFGR.

Figure A3.2 - 10

VOLTAGE GAIN OF FOREHEAD MICROPHONE PREAMPLIFIER

FREQUENCY IN CYCLES PER SECOND

VOLTAGE GAIN IN DECIBELS

Figure A3.2 - 11

APPENDIX 4.

RECEPTION SYSTEMS DEVELOPMENT

4.1 Bone Conduction Reception in Noise Fields

4.1.1 Advantage of Bond Conduction Units

1. It has the advantages of good comfort potential, of moving the transducer from the mouth area, and of fixed position, which is less susceptible to degradation of performance resulting from wrong positioning of the microphone.

2. Another advantage is the possible use of a forehead transducer as both a microphone and as a bone conduction receiver. This would decrease the number of transducers required by two, and would eliminate ear contact with its resultant discomfort. Whether the forehead transducer as a receiver will be practical depends upon the following factor: can the required intelligibility be achieved with reasonable electrical power dissipated in the receiver in jet noise, as compared to a receiver unit over or in the ear? Although a brief study of this prospect was made by RCA during Part I of this program, we feel that the ultimate potential was not clarified and that the attractiveness of the prospect merits further study. A short study to determine this is described below.

4.1.2 Theoretical Analysis of Bone Conduction Receiver on Forehead

4.1.2.1 Equivalent Circuit

A complete electro-mechanical analog diagram of a bone conduction receiver on the forehead is shown in Figure 1. From the diagram we find that for the maximum transfer of power from the receiver to the skull, Z_B, the impedance of the shunt elements C_c, C_s, C'_s and M_r should be high, and the impedance of the series elements should be low. ($C_{ss}m^*, C^*$). This means that the coupling volume, C_c, should be as small as possible, and a short calculation based on an estimate of the skin compliance C_s shows that for $ZC_c = ZC_s$ the depth of coupling volume should be less than 0.5 mm, or for all practical purposes the diaphragm should be touching the forehead.

4.1.2.2 Attempt to Verify the Electromechanical Analogy of the Forehead Bone Conduction Receiver Experimentally

In an attempt to verify this analog an experiment was devised by changing one parameter, namely the contact area and hence the contact compliance C_{ss}.

Two couplers were made with different contact areas, as shown in Figure 2. The larger area contact was actually cast over the subject's forehead to insure

a full contact. The mechanical compliance of the skin under the coupler is given by

$$C_{ss} = \frac{3 \times 10^{-5} \times 10^{-4}}{\pi (v_1 - v_2)^2}$$

where v_1 and v_2 are the outer and inner radii respectively.

The equivalent circuit values are shown in Figure 2. The compliance of the skull C_{sk} was given by Franke.

Above the resonant frequency of the mass of the driver and the compliance of the skull, which is 150 cps, the compliances C_{ss} and C_{sk} behave as a voltage divider. Hence, the force reaching the skull for a constant p, with everything else equal, should be about 17 db higher for the small contact area coupler. Hence, the bone conduction threshold should be higher by 17 db for the large area coupler as compared to the small, if the theory is correct.

Psychoacoustic bone conduction measurements were made to check the above calculations. Much care was taken to make sure that only the contact area was changed in the comparisons. The static pressure on the skin was kept constant for the two. Results are shown in Figure 3 for two subjects, JPC and MG. The results show that the bone conduction threshold remained about the same for the two couplers and hence apparently independent of contact area.

A guarded conclusion from the measurements is that the analog described in the foregoing report is not valid for calculations or detailed explanations of the function of a bone conduction receiver. A better approach would be to use an inertial type drive (no air cavity) for which the analog is simpler. Also, the discrepancy between curves 1 and 2 of Figure 6 should be resolved and further data derived on the input impedance looking into the forehead.

4.1.3 Measurement of the Differential Sound Pressure Level with the Forehead and Ear at the Threshold of Hearing

Measurements were made to determine the ratio of the bone conduction threshold on the forehead (BCTF) and the air conduction threshold at the ear. The results allow one to predict the pressure level on the forehead which will be necessary to achieve a given intelligibility. When the coupling efficiency between the transducer and the skull can be determined, the power requirements of a projected transfer will then be known.

4.1.3.1 Forehead Coupler

A coupler was made to facilitate the measurement of the BCTF. It is shown in Figure 4. The coupler is calibrated on the forehead before a threshold measurement with the probe microphone attachment.

4.1.3.2 Measurement Procedure

The experimental apparatus is shown in Figure 5. It is essentially the same as one used with our Aural Protection Program (Contract AF33(616)-3048.

One of the main problems in a bone conduction threshold test is the elimination of air borne radiation from the coupler. With the contoured foam rubber seal and a good fit, the air borne radiation seemed negligible. However, after each threshold measurement the validity was checked in two ways: (1) the subject would raise the tone above threshold and plug his ears. If the tone decreased, the test was voided; (2) the operator, who had acute hearing, would check for air borne sound at the subject's ear at threshold.

The air conduction threshold was measured using two ANB-H-1A receivers in NAF-48409-1 earphone sockets (circumaural chamois ring). The units were calibrated on the ear using a probe microphone with opening near the entrance of the ear canal. The sound pressure levels under each cushion were approximately equal at the test frequencies, ±2 db.

4.1.3.3 Results

From a calibration of the forehead and ear receivers and the attenuator settings at threshold, the difference in sound pressure level at threshold at the two locations is determined. Results are shown in Figure 6.

4.1.3.4 Discussion

The electromechanical equivalent circuit of the forehead coupler was shown in Figure 1. Because of the series and shunt elements involved, the results of the preceding section are really only applicable to a particular coupler and hence comparison to other experiments must be viewed with caution. In the Benox Report, the BCTF to Air Conduction Threshold ratio is given. It is repeated in Figure 7, Curve 1. The result of our investigation is also plotted on Figure 7, Curve 2. There is approximately a 20 db difference at middle frequencies and 10 db at high frequencies between these measurements.

The explanation of this difference, which is an important clue to the limit of usefulness of a forehead receiver, is the driving area in the two sets of experiments. In the Benox experiments the driving area was 53 cm². From the electromechanical diagram one finds that the driving area will primarily affect three elements, assuming the others are held constant. These are C_c, C_s, and M_s. Let us further assume that if the driving area is increased, the cavity volume can be held constant so C_c = constant. C_s 1/area while M_s area. Therefore, the self-resonant frequency of the skin will not change. However, below the resonant frequency of the skin under the driving area, where the skin is stiffness controlled, the impedance of the skin compliance will increase as the area increases. Therefore, the force transmitted to the skull will double as the area doubles below the resonant frequency of the skin. At high frequencies the effect of a large driving area on force transmission is not clear because the various radial and flexural modes of the skull occur.

Comparing the ratio of the areas of the Benox coupler to ours

$20 \log_{10} \frac{53}{2.2}$ = 28 db. This says if all other factors were equal, the bone

conduction threshold as measured by the larger area coupler should be 28 db lower, at least below the resonant frequency of the skin; however, at high frequencies the problem is more complex. The fact that the difference is only 20 db points to a difference in the forehead coupling compliance, errors in extrapolation of the Benox data to obtain results without occlusion of the ear canal, and, of course, different subjects taking part in the tests.

These results indicate that the ratio of the BCTF (ears unoccluded) to Air Conduction Threshold (measured with earphones) is probably limited to –60 db for a driving area of 20 to 50 cm². Hence, to achieve a 0 db S/N ratio, it would be necessary to generate 60 db more signal on the forehead than over the ear. Future study will indicate the feasibility of producing with reasonable power the levels on the forehead which will be necessary in high noise fields.

4.1.4 Factors Determining the Practicality of a Bone
        Conduction Receiver for Use in Noise Fields

4.1.4.1 Sound Pressure Levels Required in the Forehead in Noise fields

In the preceeding section we reported the results of a study to determine the difference between the air conduction and bone conduction threshold. The difference between the WEAL and Benox results is attributed to the difference in driving areas.

This data may be used to determine the sound pressure level required on the forehead to achieve any signal-to-noise ratio. For example, to achieve a 0 db S/N ratio (long-time average/average noise) as perceived by the ear in the standard 120 JN spectrum, the sound pressure levels as indicated in Figure 8 would be required. This assumes no ear protection. Assuming 30 db of ear protection, a helmet for example, the SPL as indicated by the curves of Figures 9 and 10 would be necessary.

The question arises as to whether sound pressure levels of this magnitude (140 - 200 db) generated on a small area of tissue will be damaging. The possibility of cavitation occuring in the blood vessels is discussed in the next section.

4.1.4.2 Possibility of Cavitation in the Blood Vessels under Forehead Coupler during Generation of High Sound Pressure Levels

Cavitation will occur within a liquid if a peak negative pressure exceeds the static pressure of the liquid. We are concerned that this phenomenon may occur in the operation of the forehead bone conduction receiver. The static pressure in the capillaries is known to be from 18 to 30 mm hg or .024 to .040 atmospheres. A pressure not exceeding 10 mm hg has been set as a design goal by helmet manufacturers.

If we impose the requirement that peak negative pressure on the forehead may not exceed the 10 mm hg figure above, the pressures predicted from the WEAL and Benox results with no ear protection are immediately ruled out. With 30 db of ear protection, chances for cavitation are accordingly smaller. (Compare curves 1 and 5 in Figure 9). It should be noted that the SPLs obtained from Figure 24 are a long-time average. The speech peaks may be 12 to 20 db higher (with no speech clipping)(curve 3) and with clipping and filtering the peak-to-average ratio will be approximately +8 db *curves 2). This is also indicated in the figure.

If the cavitation phenomenon can occur, then it imposes a serious limit on the usefulness of a bone conduction receiver for the intended purposes. In particular, if the attenuation of the helmet were lost, or if the noise increased substantially, communication would be lost.

4.1.4.3 Calculation of the Reactive Power in the Skin on the Forehead

The electromechanical analog of a bone conduction unit may be represented as follows:

A4-5
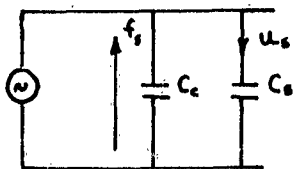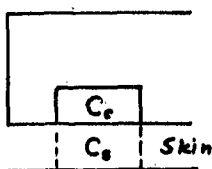
C_c = Compliance of Coupler Cavity

C_s = Compliance of Skin under Cavity

Portions are omitted which are not now of interest. The reactive power in the skin is given by $|fu_s|$ where f_s = force on skin (rms)

$$u_s = \text{velocity of skin (rms)}$$

It can be shown that the reactive power is: $P = p^2 i\ C_s S^2$

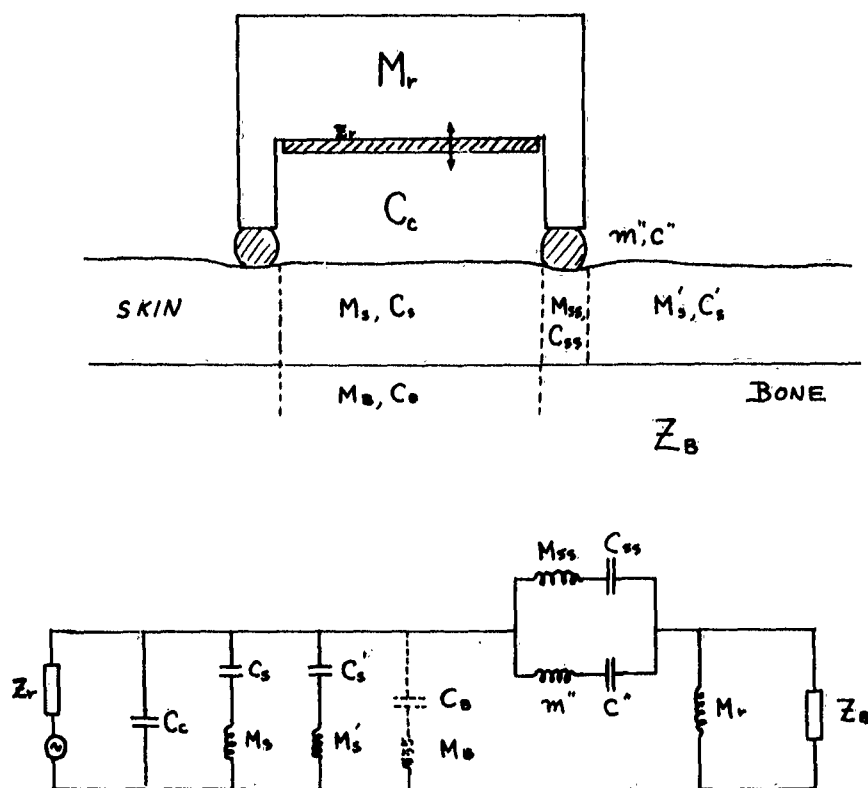where p = pressure (Newtons/m^2)   (pressure in cavity)
     ω = 2π f
     C_s = Mechanical compliance of the skin (m/Newton)
     S = The area of the skin under the cavity (driving area)(m^2)
     i = $\sqrt{-1}$

Using the results of Figure 8, the reactive power in the skin required to achieve a 0 db S/N in 120 db JN (as perceived by the hearing mechanism) may be determined. Results are shown in Figure 11.
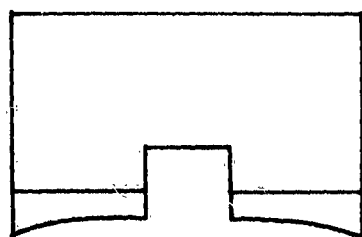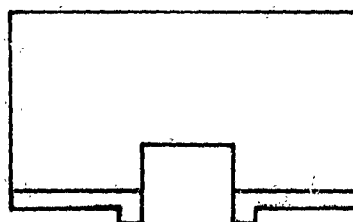
M_r = mass of coupler unit
Z_r = impedance of driving element
C_c = compliance of coupler cavity
m'', c'' = mass and compliance of coupler mounting
M_s, C_s =   "   "   "   of skin under cavity
M_{ss}, C_{ss} =   "   "   "   "   "   "   coupler edge
M'_s, C'_s =   "   "   "   "   "   around coupler
M_B, C_B =   "   "   "   "   bone under cavity
Z_B = Bone Impedance

FIGURE A4.1.1

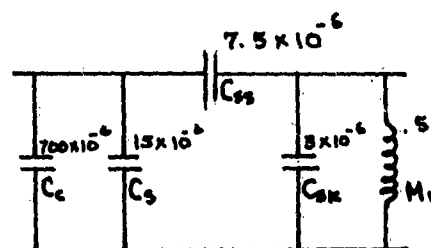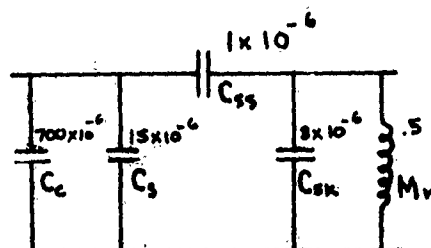# COUPLERS USED IN FOREHEAD BONE CONDUCTION THRESHOLDS

Large Contact
Area Coupler

Small Contact
Area Coupler

ELECTRO-MECHANICAL ANALOGY

C_c = Cavity Compliance

C_s = Compliance of Skin under Cavity

C_{ss} = Compliance of Skin under Coupler

C_{sk} = Skull Compliance on Forehead

M_r = Mass of Receiver Unit

Figure A4.1.2

EFFECT OF FOREHEAD CONTACT AREA ON BONE CONDUCTION THRESHOLD

This graph indicates the change in threshold when the forehead contact area was decreased from 4.61 cm² to .626 cm².

Predicted by theory

Curve 1. MG — Average of 4 runs
2. JPG — Average of 3 runs

FREQUENCY IN CYCLES PER SECOND

DECREASE IN BONE CONDUCTION THRESHOLD
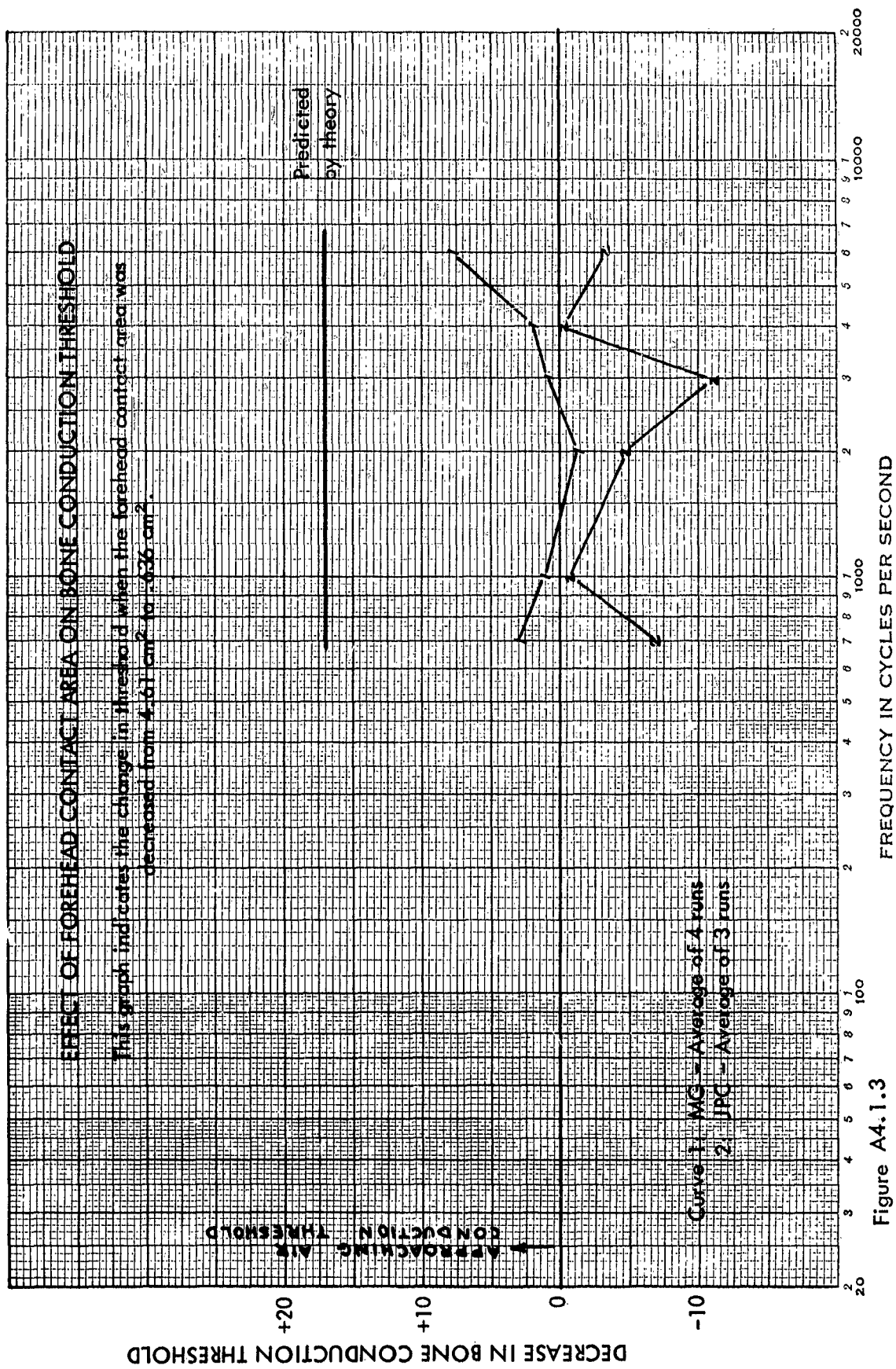
APPROACHING AIR CONDUCTION THRESHOLD

Figure A4.1.3

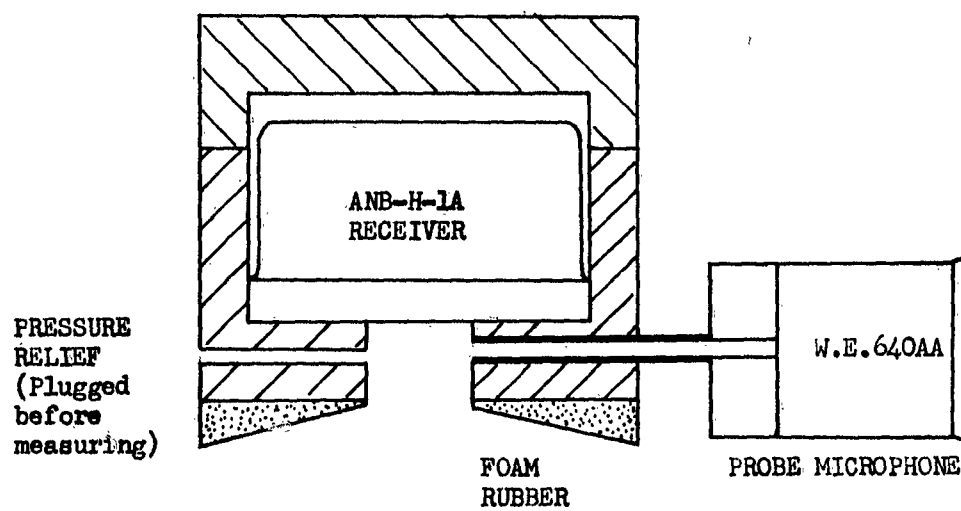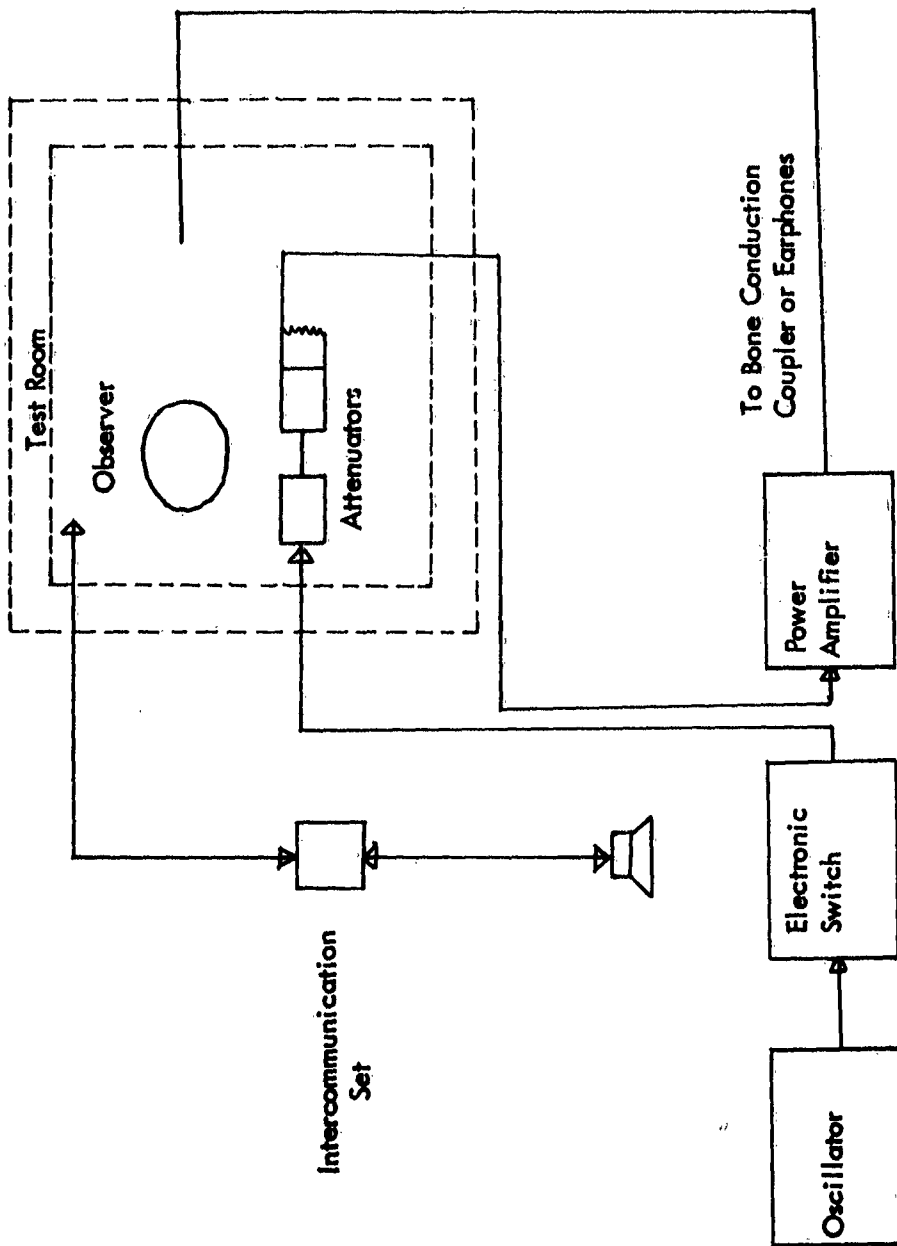FOREHEAD COUPLER USED IN BONE CONDUCTION
THRESHOLD MEASUREMENTS

Figure A4.1.4

BLOCK DIAGRAM OF TEST SETUP FOR BONE AND AIR CONDUCTION THRESHOLDS
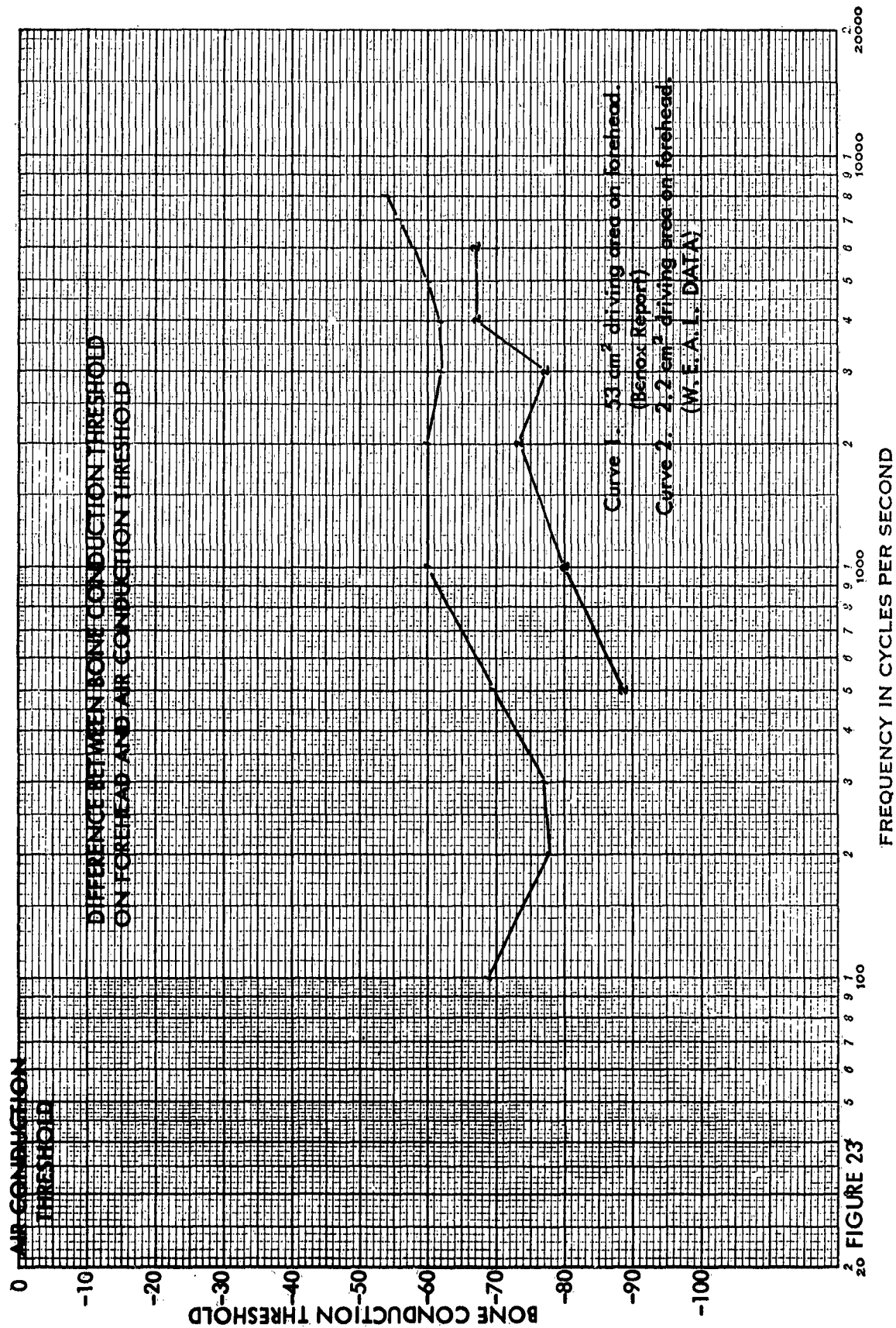
Figure A4.1.5

FIGURE 23

DIFFERENCE BETWEEN BONE CONDUCTION THRESHOLD ON FOREHEAD AND AIR CONDUCTION THRESHOLD

AIR CONDUCTION THRESHOLD

BONE CONDUCTION THRESHOLD

FREQUENCY IN CYCLES PER SECOND

Curve 1. 53 cm² driving area on forehead.
(Benox Report)

Curve 2. 2.2 cm² driving area on forehead.
(W. E. A. L. DATA)

Figure A4.1.6

Figure A4.1.7

OCTAVE PASS BANDS IN CYCLES PER SECOND
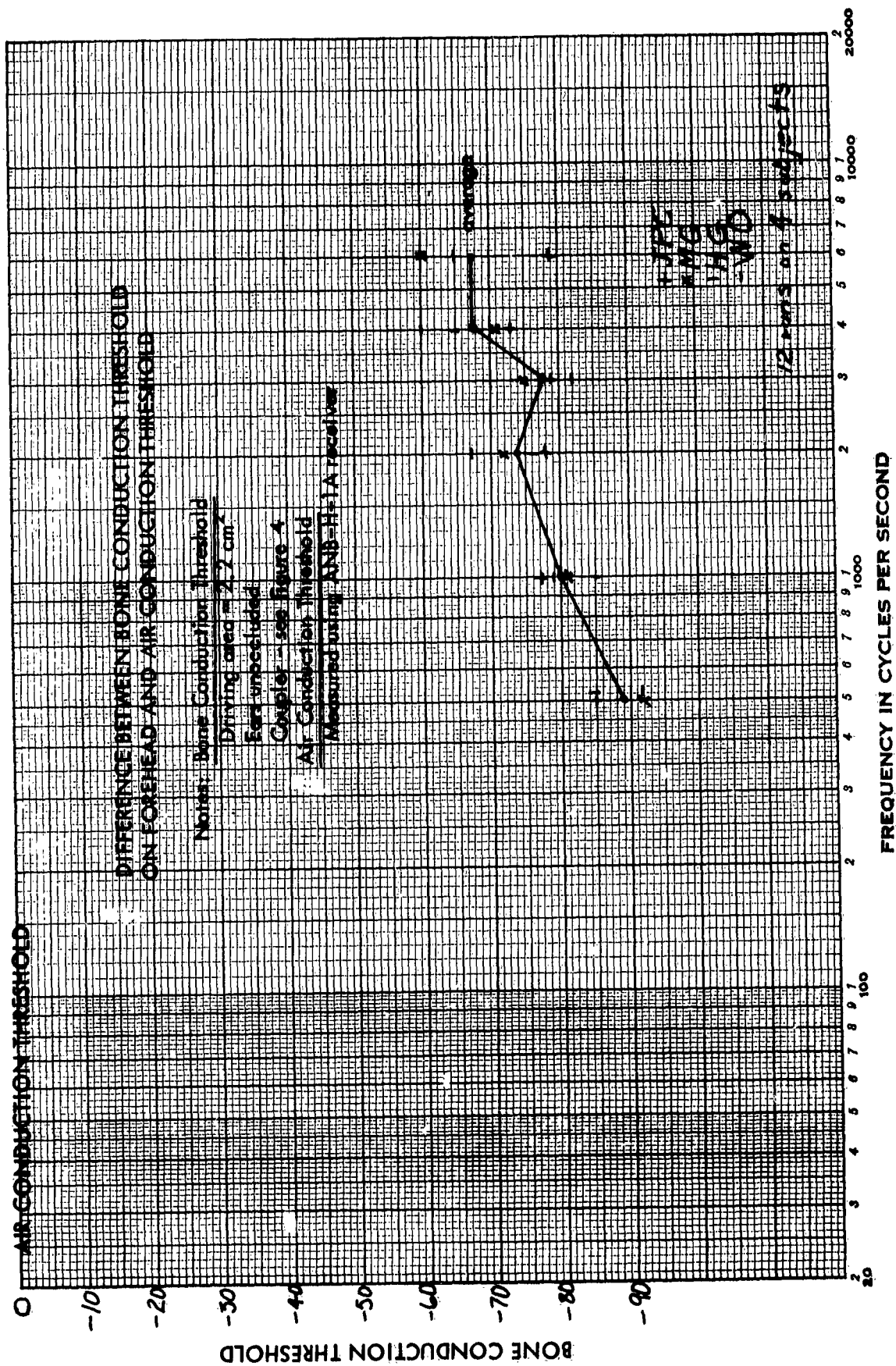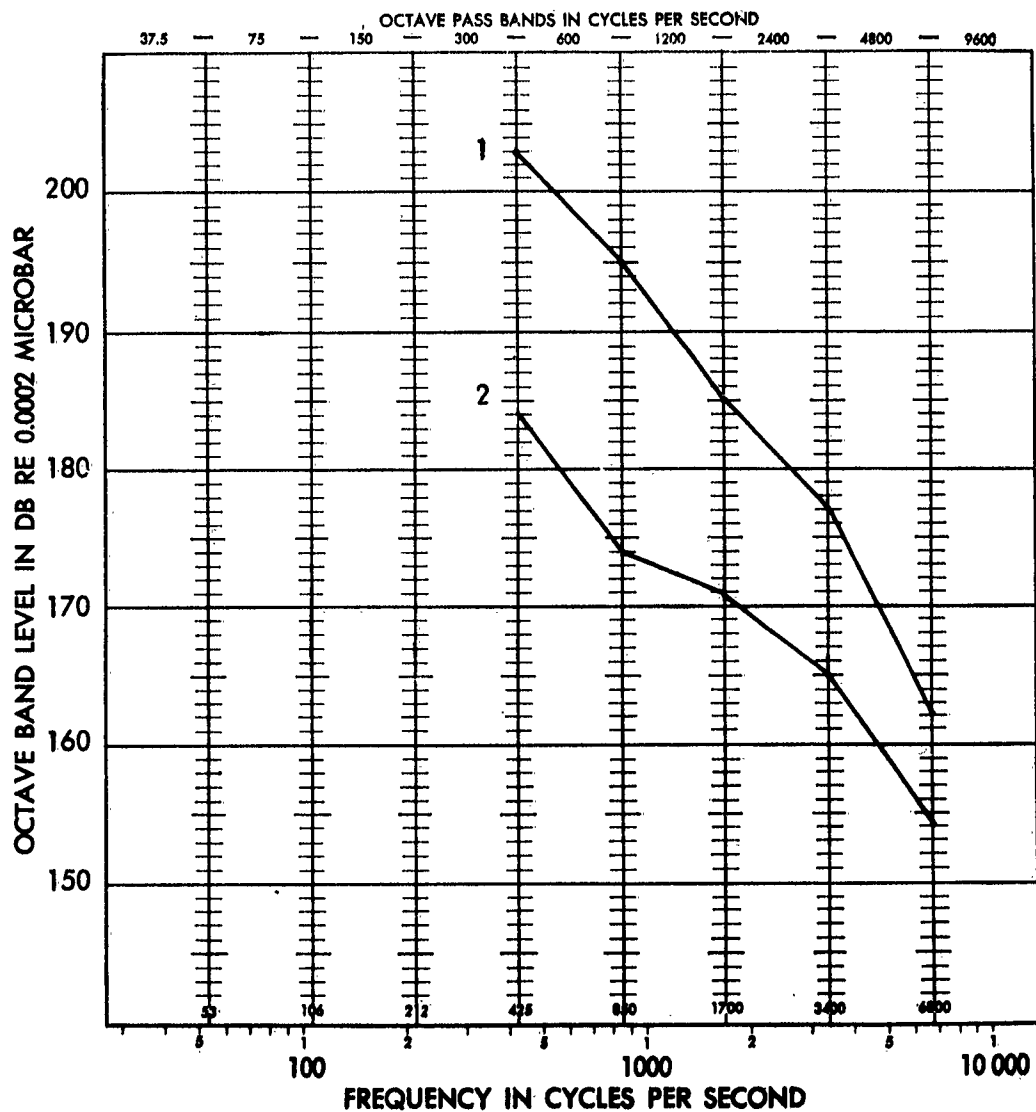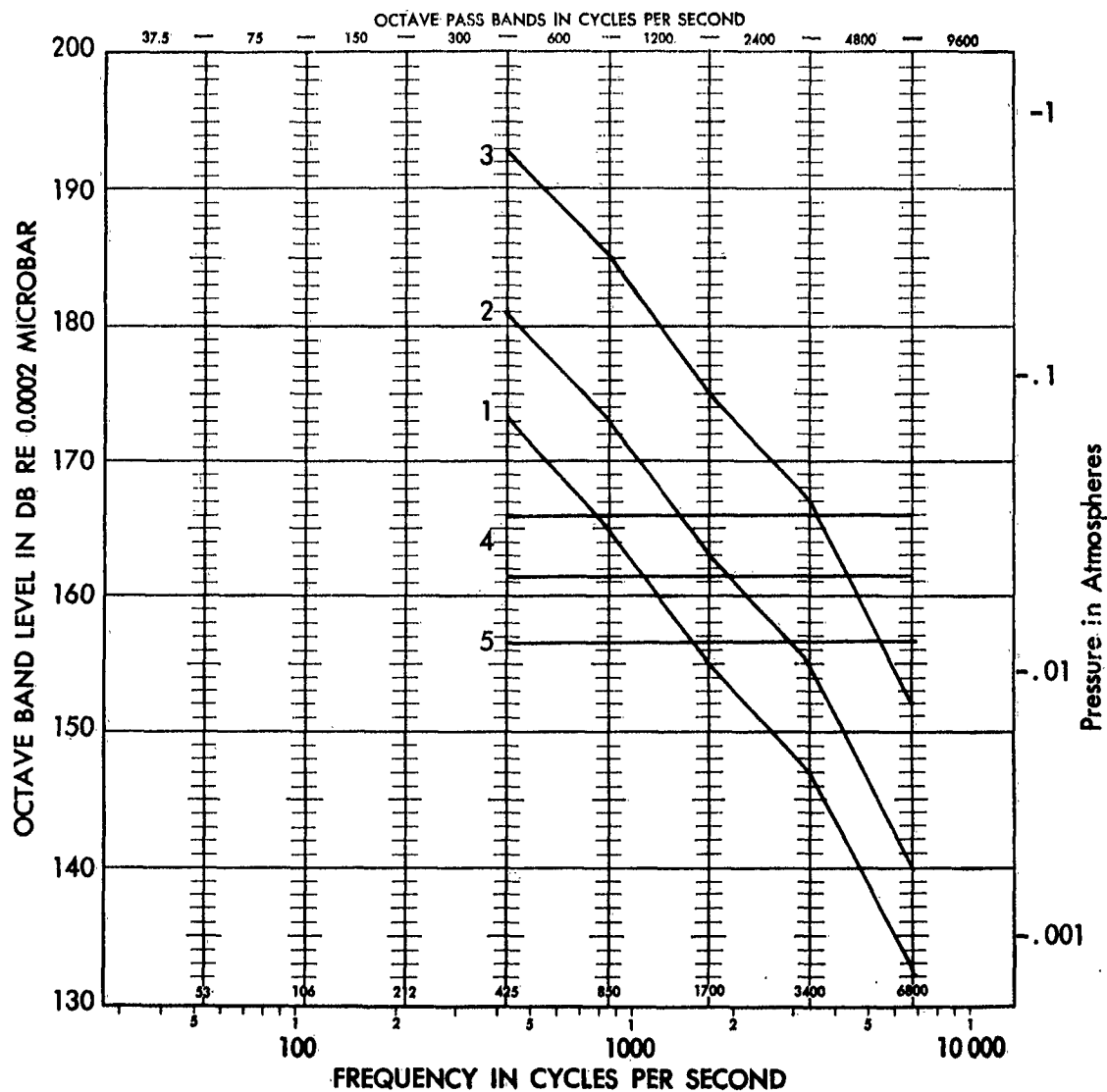
37.5 — 75 — 150 — 300 — 600 — 1200 — 2400 — 4800 — 9600

SOUND PRESSURE LEVEL REQUIRED AT FOREHEAD SURFACE
TO ACHIEVE A O DB S/N RATIO IN 120 DB NOISE AS
PERCEIVED BY THE HEARING MECHANISM.

Curve 1. Using WEAL data on difference between bone conduction
and air conduction threshold. Driving Area = 2.2 cm²
   2. Same, but using Benox data. Driving Area = 53 cm²

Figure A4.1.8

SOUND PRESSURE LEVEL ON THE FOREHEAD REQUIRED
FOR SPEECH TRANSMISSION AS SHOWN. WEAL FORE-
HEAD COUPLER. DRIVING AREA = 2.2 cm^2. PRESSURE
VALUES SHOWN RELATIVE TO BLOOD PRESSURE IN
CAPILLARIES IN VIEW OF POSSIBLE CAVITATION.

Legend:
1. Long-time average speech level required on forehead to achieve
   0 db S/N ratio in 120 db JN. 30 db helmet attenuation assumed
   between 300 - 10,000 cps.
2. Speech peaks with 8 db for 0 db S/N ratio as above.
3. Speech peaks with no clipping for 0 db S/N ratio as above.
4. Blood pressure in the capillaries (18 - 30 mm hg)
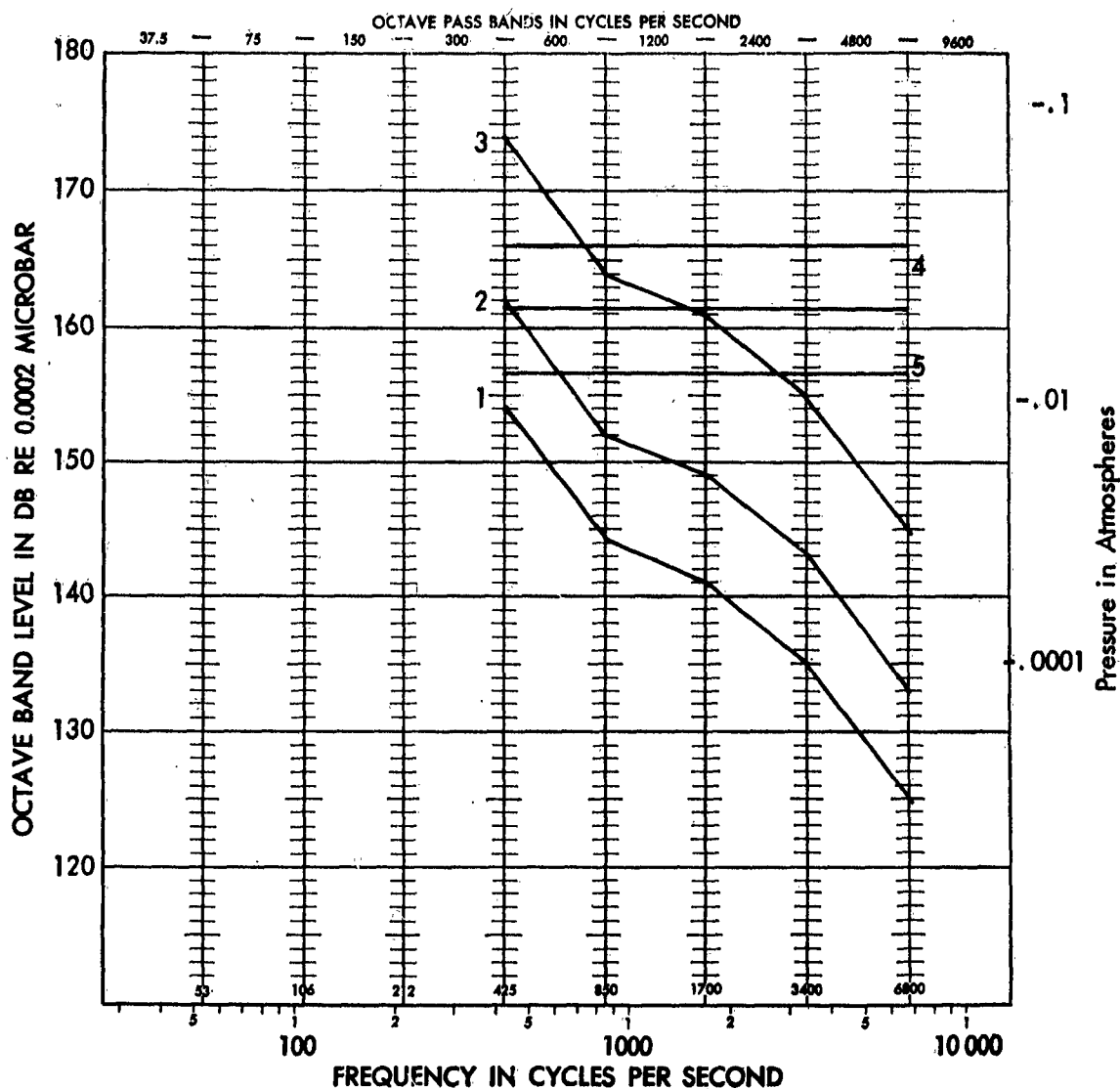5. 10 mm hg design limit for maximum pressure on skin.
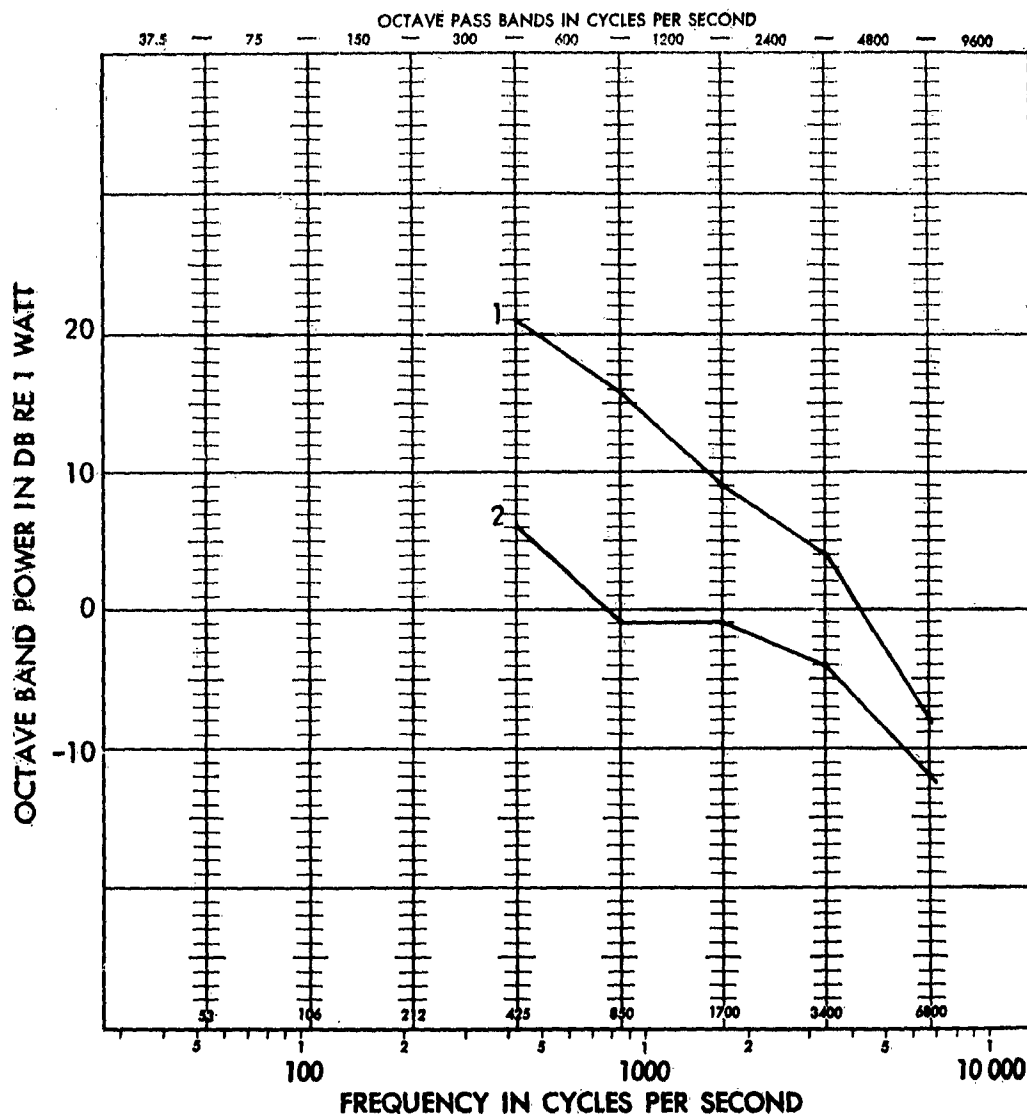
Figure A4.1.9

SOUND PRESSURE LEVEL ON THE FOREHEAD REQUIRED FOR SPEECH
TRANSMISSION AS SHOWN. BENOX FOREHEAD COUPLER. DRIVING
AREA = 53 cm^2. PRESSURE VALUES SHOWN RELATIVE TO BLOOD
PRESSURE IN CAPILLARIES IN VIEW OF POSSIBLE CAVITATION.

Legend:
1. Long-time average speech level required on forehead to achieve
   0 db S/N ratio in 120 db JN. 30 db helmet attenuation assumed
   between 300 - 10,000 cps.
2. Speech peaks with 8 db clipping for 0 db S/N ratio as above.
3. Speech peaks with no clipping for 0 db S/N ratio as above.
4. Blood pressure in the cavities (18 - 30 mm hg)
5. 10 mm hg design limit for maximum pressure on skin.

Figure A4.1.10

REACTIVE POWER IN SKIN ON FOREHEAD NECESSARY
TO ACHIEVE A 0 DB S/N RATIO (AS PERCEIVED BY HEARING
MECHANISM) IN 120 DB JN. (no ear protection).

Curve 1: WEAL Coupler.   Driving Area = 2.2 cm^2
         2. Benox Coupler.   Driving Area = 53 cm^2

Figure A4.1.11

HORN COUPLED RECEIVERS

4.2.1 Summary

It was shown in Phase I of this program that a small dynamic receiver unit could be coupled to the ear by means of an acoustic horn and deliver adequate speech level at the ears, even though the periphery of the horn is spaced slightly from the head surface.

This system offers many advantages over the conventional mounting at the ear; among these, improved comfort and potential decrease in helmet size.

An experimental program has led to the development of a practical acoustic horn which can be built into a helmet liner.

4.2.2 Brief Description of Prototype Horn

Rather than beginning with earlier experimental models of the horn, we shall first discuss the prototype horn which evolved from these models.

The horn is pictured in Figure 1. The horn was formed in Fiberglas over a plaster cast.

In order that the horn should fit several different helmets as well as provide for flexibility in flexible liners, two "hinges" have been incorporated in the horn shell. A solid transition holds the receiver unit which is mounted at the receiver unit.

The horn has been sized to permit as universal a fit as possible. The periphery of the horn mouth should completely clear the pinna, and the pinna should not contact the inner horn wall. The problem of horn sizes will be explored.

4.2.3 Incorporation of Prototype Horn in a Production Helmet

The problem arose, into what helmet should the horn be built? This laboratory has an MA-1 helmet, which is a full pressure helmet. However, this helmet is now obsolete. Later model helmets are scarce and no one helmet is yet standardized.

One currently available production helmet is the Bill Jack Sound Absorb Helmet shown in Figure 2. This helmet is for ground crew use and hence incorporates no faceplate or sealing collar, as would be found in pressurized equipment. It was decided to build the horn into this helmet. This choice was dictated by its availability and by the fact that it is a narrower helmet and will show the horn to better advantage.

The horn is embedded in the foam liner as shown in Figure 3. Any protrusion of the receiver unit will be covered as shown in Figure 4b. The liner contacts the head

around the pinna but does not touch the pinna, as shown in Figure 4a.

An alternative to the liner system is a webbing similar to that found in infantry helmets. Adjustments in size would be accomodated by adjustments in the webbing. Such a system is shown in Figure 4c.

This type of horn may also be employed to advantage in a case where additional ear protection may be required. For example, liquid seals could be incorporated around the periphery of the horn mouth. The volume associated with a standard ear muff is incorporated in the horn. Hence, a reduction in the width of the ear protector is achieved. Such a device is illustrated in Figure 4d.

4.2.4 Advantages of Horn Coupled Receivers

Several advantages of the horn coupled receivers have already been mentioned. In this section the advantages will be discussed in detail.

Prospect of Improved Comfort
Since the pinna and the flesh immediately around the ear are not contacted, improved comfort should result. Support is gained in an area away from the ear. See Figure 4a.

Decrease in Helmet Width
The width of existing helmets has been controlled by the acoustical transducers around the ears. For aerodynamic considerations as well as providing more headroom near the pilot, the helmet should be as compact as possible. Using horn coupled receivers, the helmet need be only slightly wider than the total head width (eartip to eartip). The reduction in width obtainable is illustrated in Figure 5. The width of the MA-1 helmet could be decreased 2.2 in. while the Sound Absorb could be decreased 1 in.

Center of Gravity of Helmet Lowered
In lowering the transducers to a lower helmet position, the center of gravity of the helmet is lowered. Hence, greater acceleration tolerances may be achieved.

Utilizes unused helmet space

Strengthens Helmet Shell
It may be possible to make the horns an integral part of the helmet. This will stiffen the helmet and improved acoustical attenuation may result.

Versatility
The horn may be used in a variety of situations. It may be used in helmets with a foam liner or one with a webbing. Where improved attenuation is necessary, cushions may be attached to the periphery of the horn to seal the device to the skull. It is conceivable that earmuffs may be made in a similar configuration for flight line use. This would eliminate the bulk associated with present units.

A4-8

4.2.5 Response of Curved Horn Mounted in Sound Absorb Helmet

An ANB-H-1A receiver unit was attached to the Fiberglas horn in the center, as shown in Figure 3. The receiver unit was too thick to fit inside the helmet shell. Hence a hole was cut in the rear of the helmet.

The output of the horn mounted in the helmet is shown in Figure 6. It was measured on a plaster dummy with an artificial ear and canal. This apparatus is more fully described in Section 4.2.7. Also shown on this figure are the real ear respons of two of the later AIC headsets, the H-70B and H-143. One cannot compare the physical measurement on the dummy to the subjective measurements absolutely, but at least the response using the horn is of the same magnitude as the others.

The results indicate that a horn integrated into a standard helmet can provide sufficient level for use in high noise fields when driven by a earphone unit.

4.2.6 Attenuation of Helmet Incorporating Horns

The real ear attenuation of the Sound Absorb is shown in Figure 7. The possibility of improving the attenuation will be checked.

4.2.7 Horn Development

This section consists of a description of developmental horns which di ctated the design of the prototype horn.

Horn Description

Horn #1 was developed in the exploratory phase of the program by RCA. It is shown in Figure 8a. The horn is approximately 9 in. long and is made from plastic. It was designed to be positioned opposite the ear, not to encircle the pinna.

Horn #2 was a commercial unit, the University 4401, which is used as a tweeter in high fidelity applications. It was chosen because its mouth was large enough to encircle the ear and its performance would probably indicate the maximum potential of the scheme. It is shown in Figure 8b.

Horn #3 was the first step toward a feasible design. It was constructed of sheet metal 8.5 in. long and had a cutoff of 200 cps. The horn mouth was designed to barely clear the pinna. It is shown in Figure 8c.

Horn #4 was a curved version of #3. It was designed to fit inside the MA-1 helmet. It served as a guide in making the plaster cast from which the prototype horn was made. It is similar in appearance to the Fiberglas horn previously described.

Experimental Procedure

Most of the measurements reported below were made using a 640AA Western Electric microphone mounted at the base of a dummy ear canal. The device and a

block diagram of the apparatus are shown in Figure 9.

Experimental Results

Horn #1 (RCA)

The frequency response of this horn as driven by a Shure MC-115 magnetic receiver is shown in Figure 10 as a function of distance from the pinna. Note that the response is for 1 mw reactive power (1 v across 1000 ohms inductive at 1000 cps). The levels obtained at low and high frequencies are comparable to receiver locations at the ear. In the midrange the response is much higher.

Horn #2 (University 4401)

Measurements were made on this horn particularly to study the effect of horn termination on response. Normally this horn is terminated in free space. For the horn coupled receivers, the termination is the pinna and the side of the head.

The response of this horn is shown in Figure 11. The results indicate that the presence of the skull and pinna actually increase the output, particularly in the mid-frequency region.

Horn #3 (Straight Sheet Metal)

The results obtained on horns #1 and #2 encouraged us to fabricate a horn whose mouth clears the pinna.

The response of this horn using the University 4401 horn is shown in Figure 12. The coupling efficiency of this horn is actually superior to the University horn.

The 4401 driver is naturally too large for use in a helmet. Hence, a headphone driver (ANB-H-1A type) was used to drive the horn. This unit is 2 in. in diameter, 1 in. thick and weighs 100 grams. Smaller receiver units are available which are 1 in. in diameter, 38/ in. thick and weigh 10 grams. The response of the ANB-H-1A unit is compared to the University 4401 in Figure 13. The output of the 4401 is 10 to 15 db higher below 2500 cps. However, the response with the horn with the ANB-H-1A is still superior to receivers mounted opposite the ear, such as the H-70B/AIC (MX-2088/U ear cushion) or the H-143/AIC in H-158 headset, as also shown in the figure.

The virtue of the horn coupled receiver unit is illustrated further in Figure 14. Here the ANB-H-1A receiver is coupled to the ear using three techniques: (1) horn coupled, (2) hard walled coupling volume adjacent to ear, (3) coupling volume as found in a typical helmet liner, as shown in Figure 15. The results indicate that the horn coupling is actually slightly more efficient than the receiver mounted in the volume opposite the ear. The difference between curves 2 and 3 is due to the large amount of absorption contributed by the helmet liner.

A4-10

Horn #4 (Curved Sheet Metal)

The next step was to incorporate a horn into a helmet liner. A curved sheet metal horn was formed which fit into the MA-1. Its response is compared to Horn #3 with the University 4401 in Figure 16. Their responses are similar except at low frequencies due to the additional volume of the horn and the larger distance of the horn perimeter from the skull.
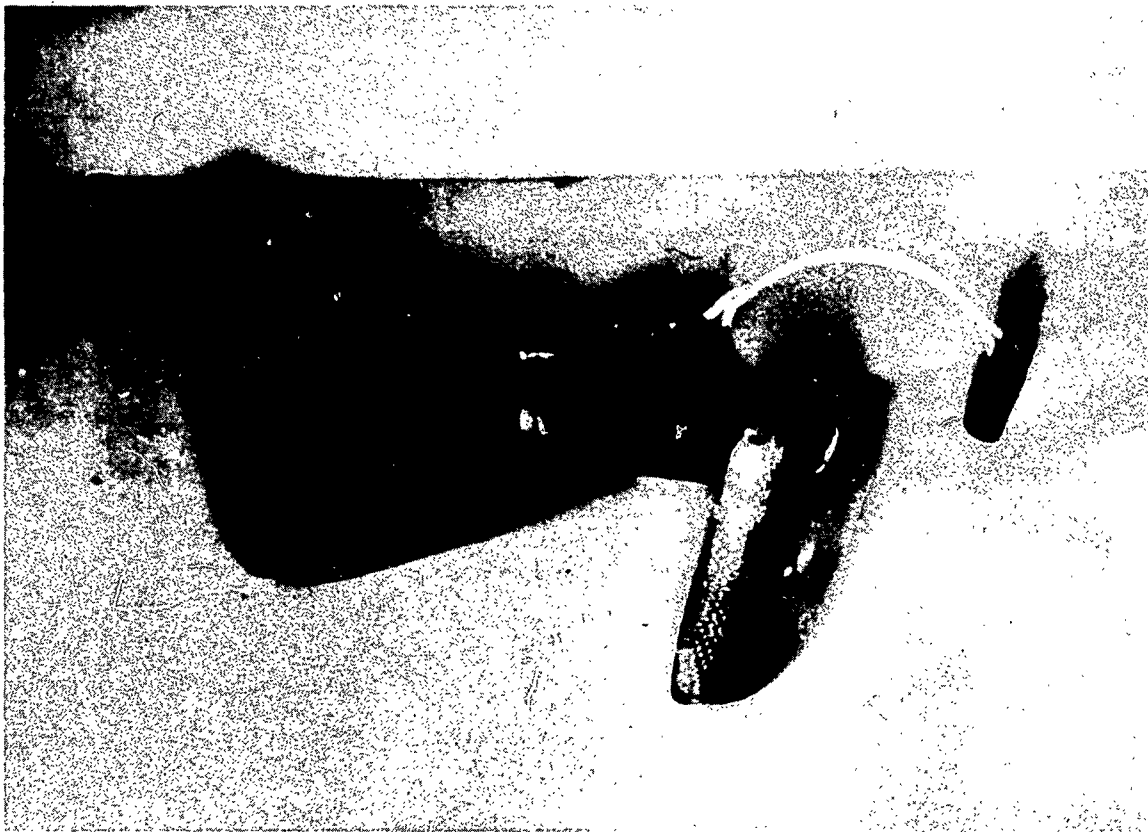
Figure A4.2-1

PROTOTYPE HORN UNIT

Figure A4.2-2
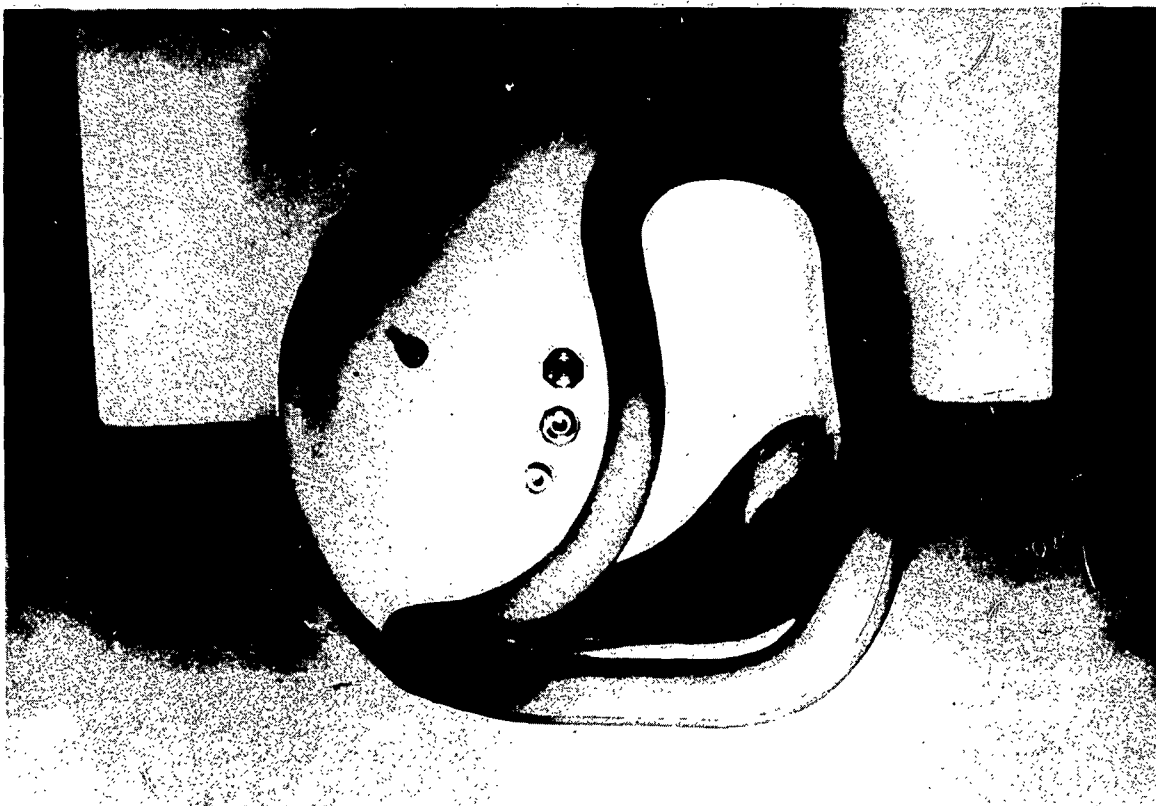
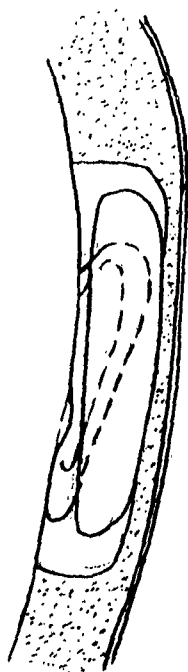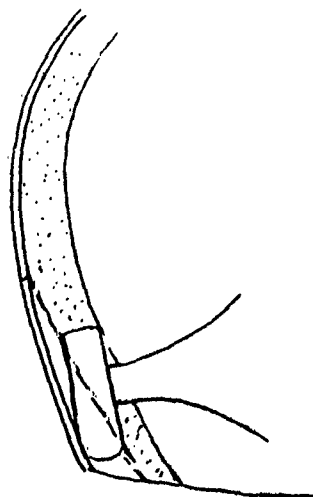BILL JACK SOUND ABSORB HELMET

Figure A4.2-3

PROTOTYPE HORN BUILT INTO BILL
JACK SOUND ABSORB HELMET
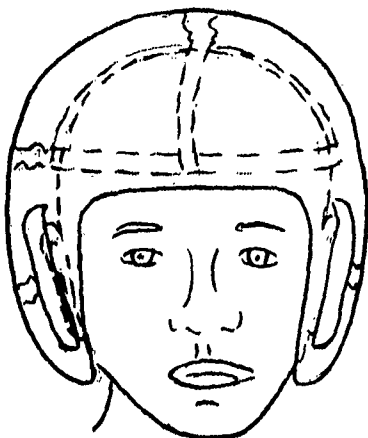
(a)

Section showing horn coupled
Receiver at ear. Note helmet
liner contacts area away from
ear for support

(b)

Finished mounting arrangement
for receiver unit in Sound Absorb
Helmet

(c)

Use of horn coupled receivers
in helmet supported by harness only
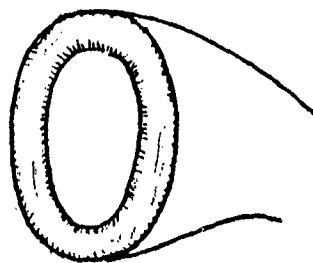
(d)

Incorporation of liquid seal
around horn mouth. Width of
device is narrower than
conventional liquid seal muffs

FIGURE A4.2-4

Head Breadth (ear-ear
Tip) 50 Percentile
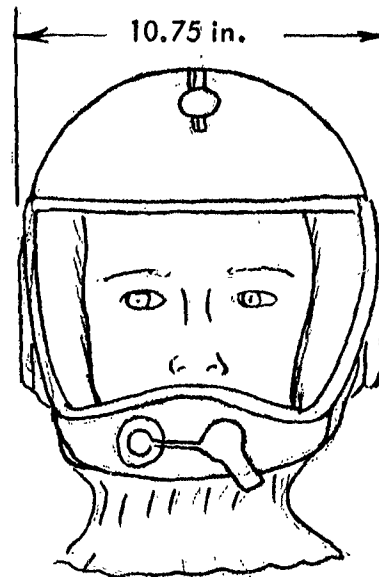
MA-1 Helmet
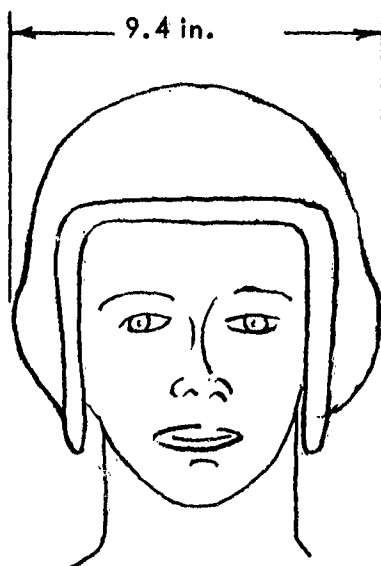
Bill Jack Sound Absorb

(incorporating horn-
coupled receivers)
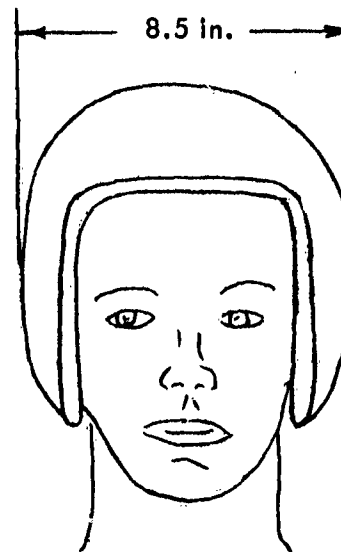
Potential Helmet

(incorporating horn-
coupled receivers)

NOTE: All helmets medium size.

Figure A4.2-5

Figure A4.2-6

FREQUENCY IN CPS

Sound Pressure Level in db., 1 mw Input

Equivalent Free Field Sound Pressure Level
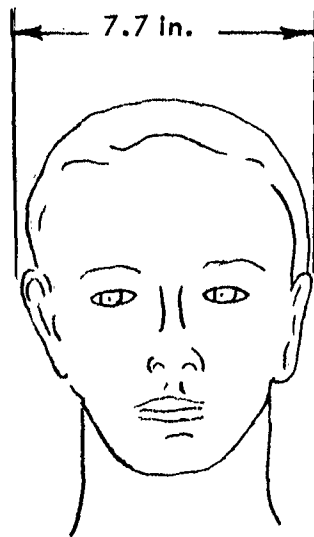
1. ANB-4-1A Driver, WEAl Fiberglas Horn in Bill Jack Helmet
   SPL Measured at Base of Dummy Ear Canal (use left scale)
2. H-70B/AIC Driver, MX-2088/U Cushion, Equivalent Free Field Ear Response (use right scale)
3. H-143/AIC Driver, H-158 Cushion, Equivalent Free Field Ear Response (use right scale)

REAL EAR ATTENUATION OF BILL JACK SOUND ABSORB HELMET
INCORPORATING HORN-COUPLED RECEIVERS

Average of 4 runs, 2 on each of 2 observers

ATTENUATION IN DECIBELS

FREQUENCY IN CYCLES PER SECOND

Figure A4.2-7

HORNS USED IN EXPERIMENTAL PROGRAM
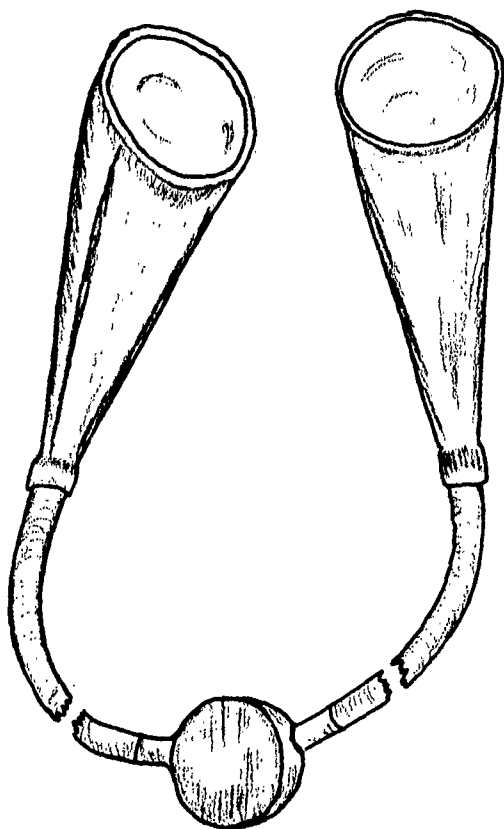
Horn No. 1 (RCA Horn)
(a)
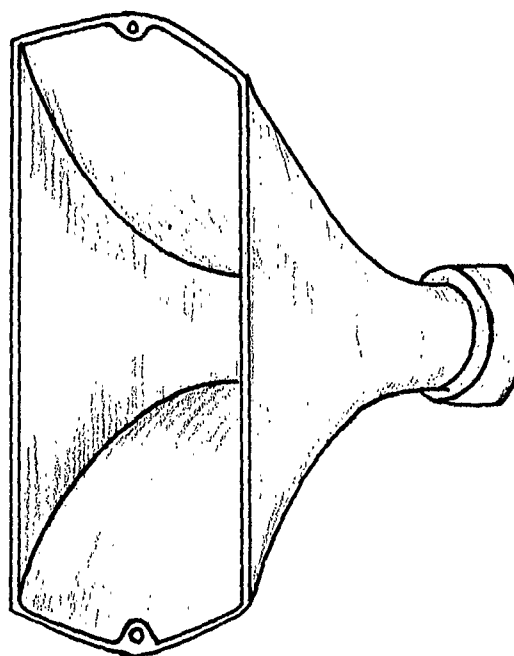
Horn No. 2(University 4401)
(b)
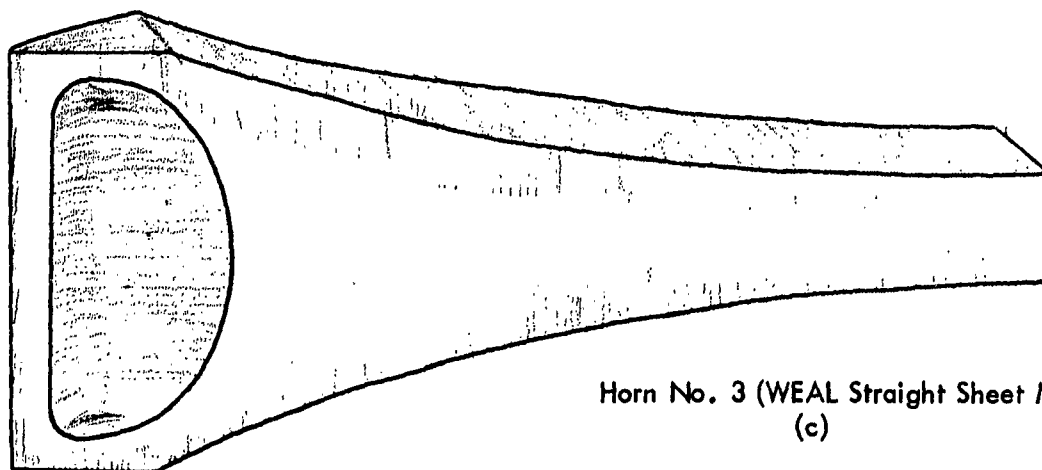
Horn No. 3 (WEAL Straight Sheet Metal)
(c)

Figure A4.2-8

DUMMY EAR AND CANAL USED
TO PERFORM FREQUENCY RESPONSE
MEASUREMENTS DESCRIBED IN TEXT

Dummy Plaster Head

Coupler

WE
640AA

Preamp

Ear Canal

Power
Amplifier

Condenser
Mic. Compl.

Oscillator

Voltmeter
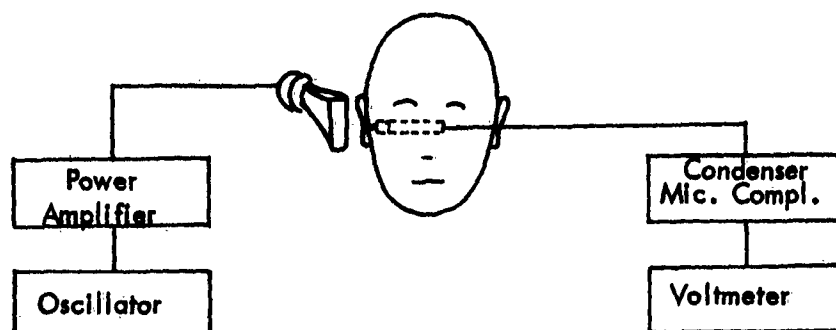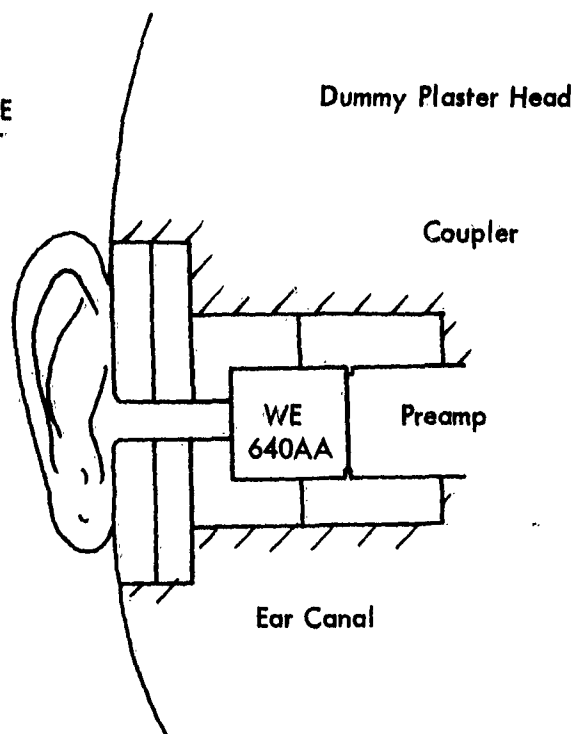
Electrical Apparatus for Response Measurements on Horns

Figure A4.2-9

Figure A4.2-10

FREQUENCY RESPONSE OF HORN NO. 2 (UNIVERSITY 4401 HORN), UNIVERSITY 4401 DRIVER
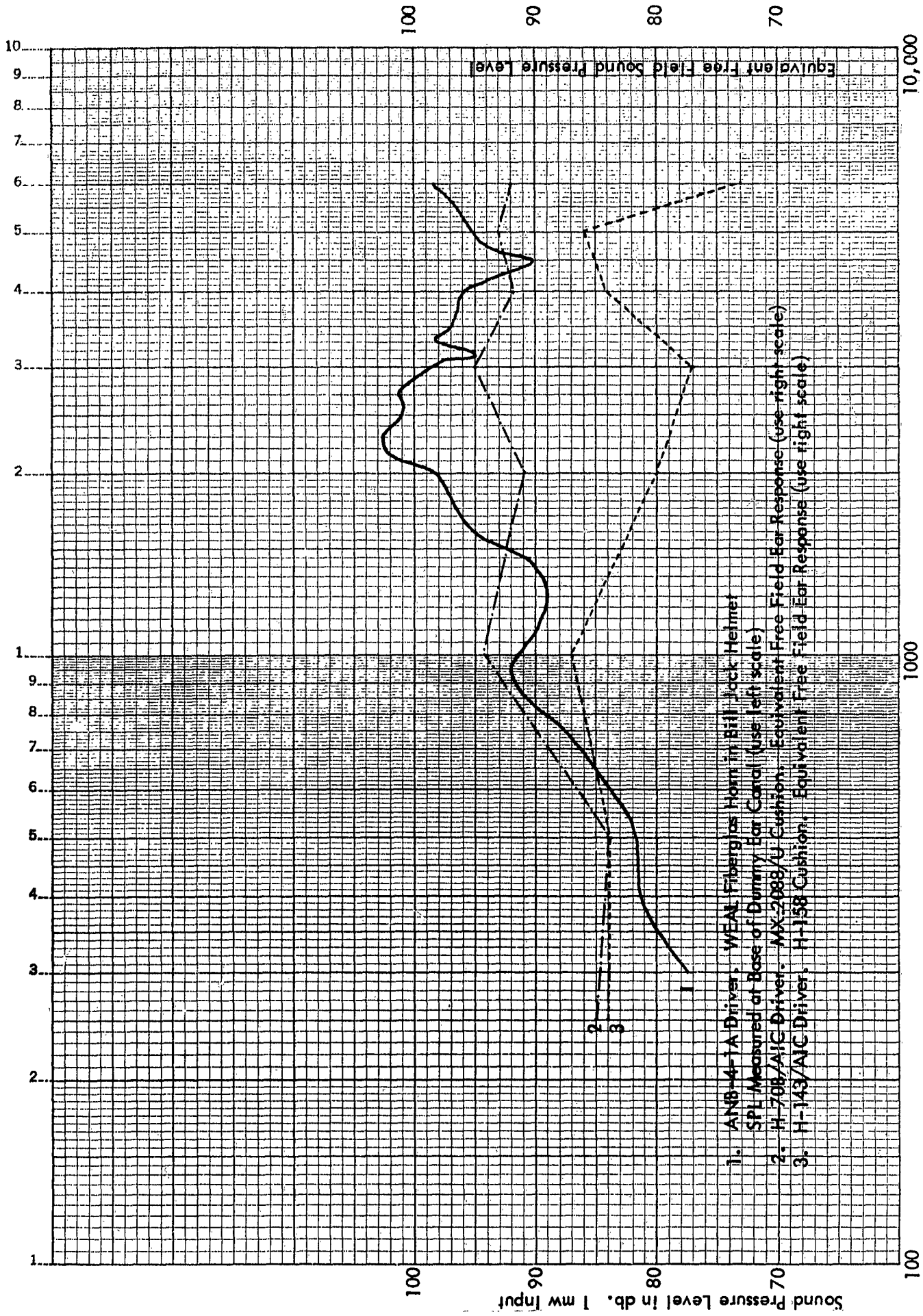
LEGEND:
1. Horn Surrounding Pinna. Perimeter of Horn 1/8 in. from Skull.
2. Same as 1., but Horn 1 in. from Skull.
3. Response in Plane of Horn Mouth. Head not Present.

1 mw Input

FREQUENCY IN CPS

Sound Pressure Level in db. 1 mw Input

Figure A4.2-1

FREQUENCY RESPONSE OF WEAL HORN NO. 3, STRAIGHT SHEET METAL HORN), UNIVERSITY 4401 DRIVER

LEGEND:
1. Horn 1/8 in. from Skull
2. Horn 3/4 in. from Skull
3. Response in Horn Mouth, Head not Present

1 mw Throat

FREQUENCY IN CPS

Sound Pressure Level in db for 1 mw Input

Figure A4.2-12

FREQUENCY RESPONSE OF HORN NO. 3 (STRAIGHT SHEET METAL) USING TWO DIFFERENT DRIVER UNITS.

LEGEND:
1. University 4401 Horn Driver
2. P/O H-3/ARR-3 CTE Headphone
(AN8H-1H Type)

1 mw Input

Perimeter of Horn 1/4 in. from Dummy Head

FREQUENCY IN CPS

Sound Pressure Level in db., 1 mw Input

Figure A4.2-13

RESPONSE AT BASE OF DUMMY EAR CANAL USING THREE
COUPLING TECHNIQUES. DRIVER UNIT: P/O H-3/ARR-3 CTE (ANBH-1A TYPE)

LEGEND:
1. Driver Attached to WEAL Horn No. 3
   (straight sheet metal). Perimeter of
   Horn 1/4 in. from Skull. Coupling
   Volume = 191 cc

2. Driver Attached to Sheet Metal Coupling. Volume Opposite Ear.
   Volume = 90 cc. Perimeter of coupling Spaced 1/4 in. from Skull.

3. Driver Mounted in MA-1 Helmet Liner Opposite Ear. Coupling
   Volume = 76 cc

4. Driver Mounted in 2 cc Coupler

See Figure 15 for Diagram of
Coupling Conditions

FREQUENCY IN CPS

Sound Pressure Level In db. 1 mw Input

Figure A4.2-14

Horn Coupled Receiver. Approximate Coupling Volume =
190 cc. Spacing 1/4 in. (curve 1)
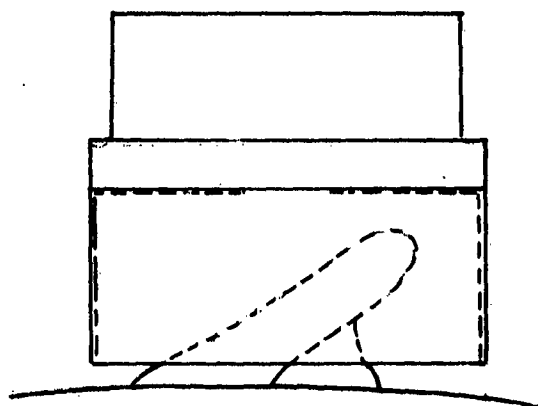
Sheet Metal Ear Cup. Coupling
Volume = 90 cc. (curve 2)
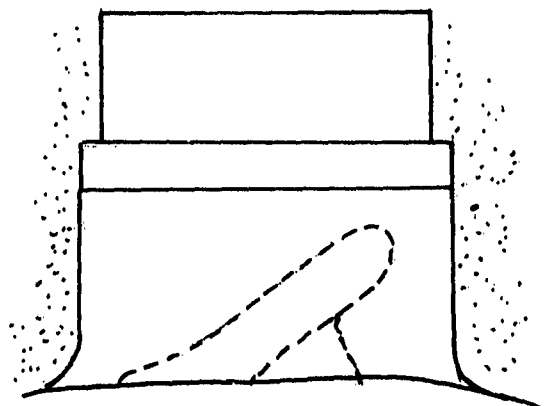
Receiver Mounted in MA-1
Helmet Liner. Coupling
Volume = 76 cc. (curve 3)
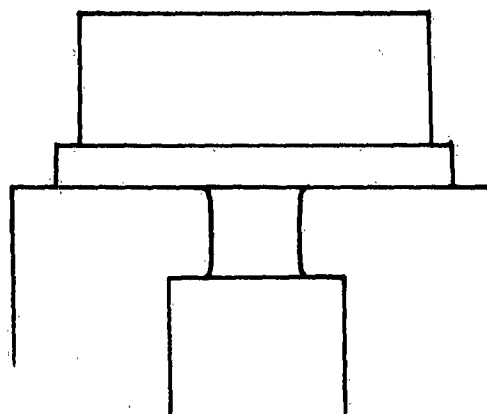
Receiver Mounted on 2 cc Coupler (curve 4)

Figure A4.2-15

COMPARISON OF RESPONSE OF HORN NO. 3
(STRAIGHT) AND NO. 4 (CURVED SHEET METAL)- UNIVERSITY 4401 DRIVER

LEGEND.
1.- Horn No. 3 — (Straight)
2.- Horn No. 4 — (Curved)

Both Horn Perimeters 1/4 in. from Skull

FREQUENCY IN CPS

Sound Pressure Level in db., 1 mw Input

Figure A4.2-16

4.3 Study of Loudspeaker Mounted Inside
Experimental Plastic Helmet

4.3.1 Introduction

It was shown in Phase I of this contract that a small loudspeaker unit can be mounted in unused space within the helmet and provide sufficient sound level for good performance. The helmet is spaced away from the head without contact, and there is no further acoustic coupling.

In the series of measurements to be described, the spherical plastic helmet developed during Phase I was used. The purpose of these measurements was to elaborate on the simple tests which were conducted previously. It was hoped that the results of these experiments will yield information as to location of transducers and absorption for optimum performance.

There are two factors which must be considered in the acoustical design of a speech reception system in a helmet of this type. These are crash protection and vision requirements. Since the heat must move freely within this helmet, the location of crash protection (which must also serve as acoustical absorpt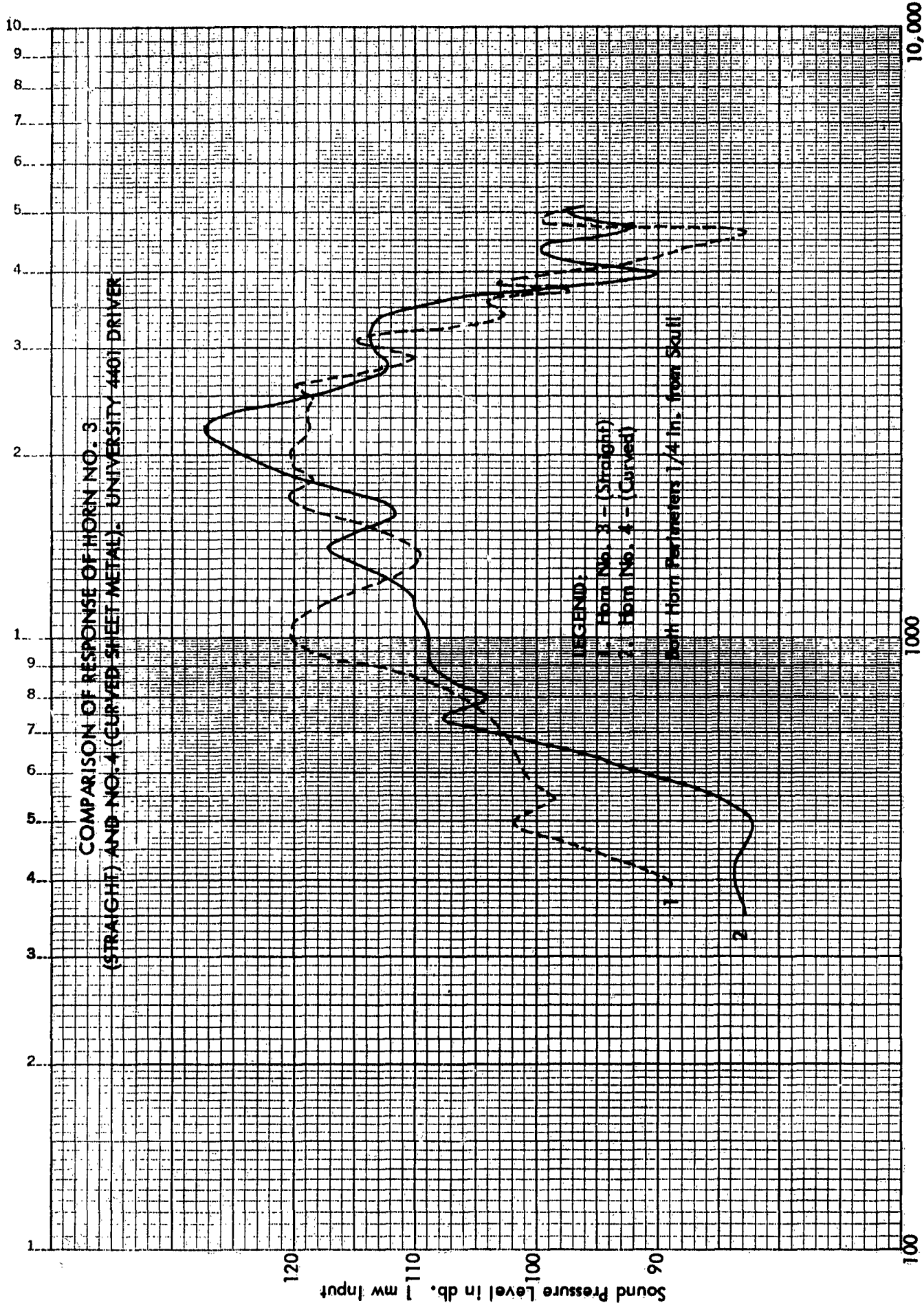ion) and transducers is limited, if peripheral vision is not to be impeded. It is possible that some crash protection may be needed on the head itself.

The response of a loudspeaker radiating into a helmet worn by a subject as measured at some point will be extremely complex due to the normal modes of vibration which are determined by the boundary conditions. The field will also be changed as the head is moved within the helmet.

Hence, proper acoustical design of a loudspeaker within a helmet is indeed a complex one. Due to this complexity, measurements were made to compare loudspeaker locations, absorption, placement, etc. The results will guide the ultimate design of a prototype helmet, which will incorporate factors for optimum crash protection, visual considerations, and acoustical design.

4.3.2 Basic Loudspeaker Design

A 3-in. Quam loudspeaker, considered typical of small direct radiator loudspeakers, was chosen for these measurements. The back of the loud-speaker was enclosed in a cylindrical shell in which absorbing material was added. The axial frequency response of the loudspeaker in the shell mounted on a flat baffle is shown in Figure 1.

4.3.3 Response of Loudspeaker within Helmet

The frequencies of the normal modes as well as the pressure distribution within a spherical shell are well known. However, when a head is placed within the helmet, an additional boundary is introduced which will change this picture. The pressure distribution and resonant frequencies will also change somewhat as the head moves within the helmet.

The approach that was taken was to measure the response of the loudspeaker in the helmet at a fixed point within the helmet. The position of the head relative to the helmet was the same for all measurements. Hence, comparisons of the response for various configurations could be made. However, this response would vary considerably if the head position was changed.

A dummy plaster head, with shoulders to which the back of the helmet was sealed, was employed to give controllable conditions. A probe microphone was used to measure the response. A photograph of the apparatus is shown in Figure 2.

Three different loudspeaker mounting locations were employed, as shown in Figure 3. The response was measured at both the ear and the mouth because of the acoustic feedback problem. Results are shown in Figures 4 and 5. Because no absorption was present and the dummy head is hard, pressure differences on the order of 50 db resulted. No measurements were made above 2000 cps because of the complexity of response.

4.3.4 Effect of Added Absorption within the Helmet on Loudspeaker Response

Measurements were made to determine the effect of absorption on the loudspeaker response. Two locations were chosen as shown in Figure 3. The choice of absorption was arbitrary - consisting of cotton-like material compressed into pads from 1 to 2 inches thick. Additional studies correlated with crash protection requirements would be necessary to find the best material. Hence, the absorption chosen was only chosen to illustrate the phenomena. Results are shown in Figures 6, 7, 8, 9 and 10.

In examining this data it should be stressed that smooth response of the ear is not completely sufficient. The response at the lips will in part determine the gain limitation within the helmet due to acoustic feedback.

The results clearly indicate the response at the ear is smoothest when the loudspeaker is mounted opposite it. However, the response of the opposite ear is considerably lower, especially from 1000 to 3000 cps. This mounting

position also slightly interferes with peripheral vision. Hence, it may be possible to use two small loudspeakers mounted slightly to the back of each ear.

The second choice for smooth response at the ears is the top-mounted position with absorption at the helmet base. The response at both ears is the same because of symmetry; therefore, one loudspeaker would suffice.

The rear-mounted position shows a large peak in response at 450 cps and very low response between 1000 and 2000 cps and is, therefore, not recommended.

The results indicate that the response at the mouth is smoothest when the loudspeaker is mounted either opposite the ear or on top of the helmet.

Since there will be a space limitation opposite the ears or on top of the helmet, the development of a flat electrostatic loudspeaker for helmet use takes on new significance. We are in the process of exploring the potentialities of an unbiased push-pull electrostatic loudspeaker which, if practical, will eliminate the common objection to electrostatic units - the very high bias voltage.

4.3.5 Power Requirements.

An approximation of the loudspeaker power requirements to produce an overall sound pressure level may be obtained from Figures 6 to 10. Since there are considerable peaks and dips in response, an average response was estimated rather than taking the sensitivity at 1000 cps, for example.

The results are tabulated in Table I, Part A. In order to establish a 0 db S/N ratio in 120 db in outside the helmet and assuming 30 db helmet attenuation in the speech bands, the power requirements as indicated in Table I, Part B would be necessary. All are well within the power capacity of the speaker.

In summary, the response of a loudspeaker within a helmet is extremely complex, being a function of head position, loudspeaker placement and absorption. Response at both the ears and the lips must be considered. We have endeavored to show the effect of changing these parameters with the purpose of determining optimal locations for transducers and absorption. The results indicate that the loudspeaker should be mounted opposite the ear or at the top of the head. Such locations will depend upon the development of a thin, lightweight transducer, presumably of the electrostatic type.
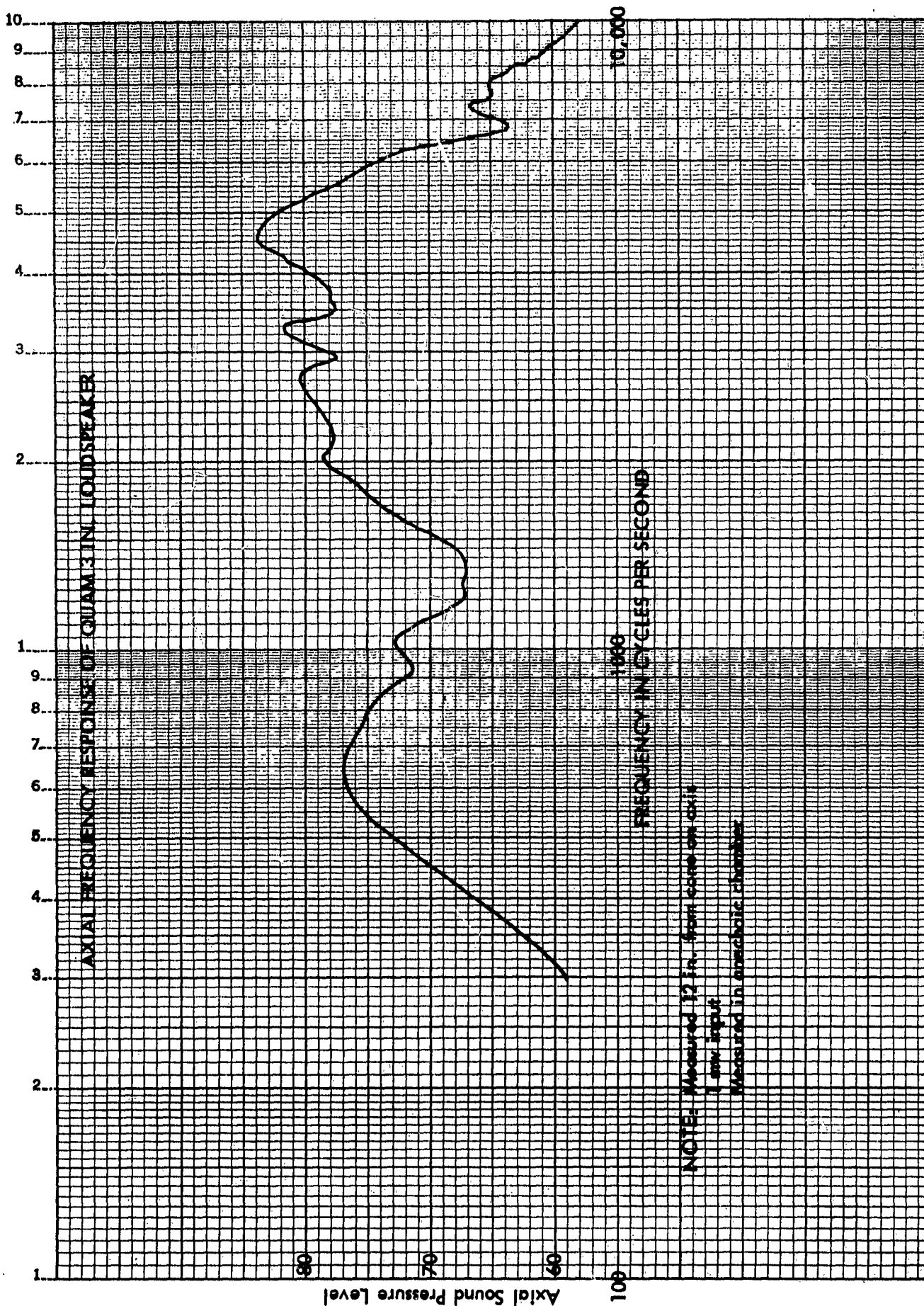
Figure A4.3-1

Figure A4.3-2
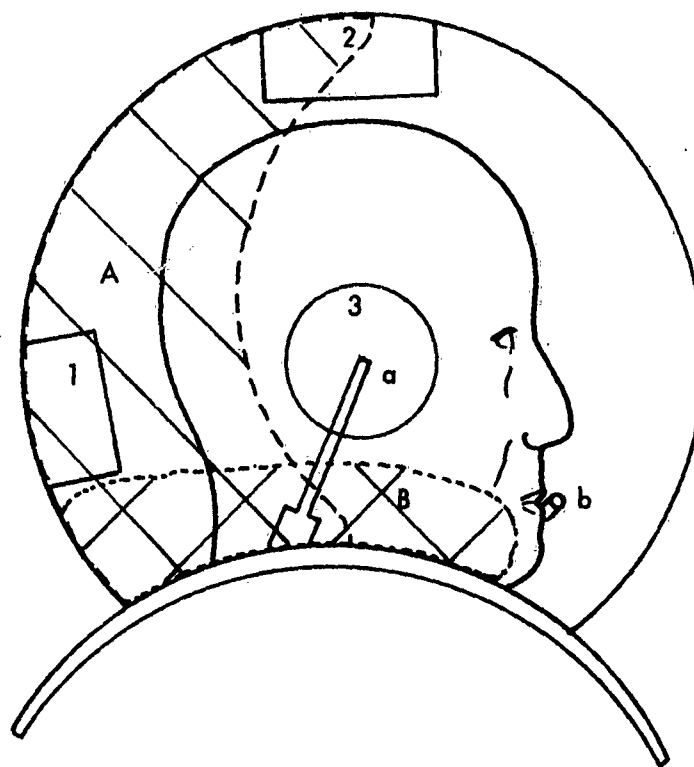
**DIAGRAM SHOWING LOUDSPEAKER, MICROPHONE
AND ABSORPTION LOCATIONS USED IN HELMET EXPERIMENTS**

Loudspeaker Locations:
1. In rear
2. On top
3. Opposite right ear

Microphone Positions:
a. Opposite right ear
b. Next to mouth

Absorption Locations:
A. Covering rear portion of helmet only
B. Around base of helmet only

Figure A4.3-3

RESPONSE OF QUAM MICROPHONE IN PLASTIC HELMET – NO ABSORPTION
MICROPHONE AT RIGHT EAR

Legend:
1. Loudspeaker at rear
2. Loudspeaker at top
3. Loudspeaker opposite right ear

1 mw at 1000 cps

FREQUENCY IN CYCLES PER SECOND

SOUND PRESSURE LEVEL IN DB

Figure A4.3–4

RESPONSE OF QUAM LOUDSPEAKER IN PLASTIC HELMET – NO ABSORPTION
MICROPHONE AT MOUTH

Legend:
1. Loudspeaker at rear
2. Loudspeaker at top
3. Loudspeaker at right ear

1 mw input at 1000 cps

SOUND PRESSURE LEVEL IN DB

FREQUENCY IN CYCLES PER SECOND

Figure A4.3-5

RESPONSE OF QUAM LOUDSPEAKER IN PLASTIC HELMET
ABSORPTION AT BASE OF HELMET
MICROPHONE AT RIGHT EAR

SOUND PRESSURE LEVEL IN DB

FREQUENCY IN CYCLES PER SECOND

1 mw input at 1000 cps

Legend: 1. Loudspeaker at rear
        2.   "   top
        3.   "   opposite right ear

Figure A4.3-6

RESPONSE OF QUAM LOUDSPEAKER IN PLASTIC HELMET
ABSORPTION AT BASE OF HELMET
LOUDSPEAKER AT RIGHT EAR

SOUND PRESSURE LEVEL IN DB

FREQUENCY IN CYCLES PER SECOND

1 mw input at 1000 cps

Legend: 1 Microphone at left ear
        2 Microphone at right ear

Figure A4.3.7

RESPONSE OF QUAM LOUDSPEAKER IN PLASTIC HELMET
ABSORPTION AT REAR OF HELMET
MICROPHONE AT RIGHT EAR

1 mw input at 1000 cps

FREQUENCY IN CYCLES PER SECOND

SOUND PRESSURE LEVEL IN DB

Legend:
1. Loudspeaker at rear
2. " " top
3. " " right ear

Figure AA-3-8

RESPONSE OF QUAM LOUDSPEAKER IN PLASTIC HELMET
ABSORPTION AT BASE OF HELMET
MICROPHONE AT MOUTH

FREQUENCY IN CYCLES PER SECOND

1 mw input at 1000 cps

SOUND PRESSURE LEVEL IN DB

Legend: 1. Loudspeaker at rear
2. Loudspeaker at top
3. Loudspeaker opposite right ear

Figure A4.3-9

RESPONSE OF QUAM LOUDSPEAKER IN PLASTIC HELMET
ABSORPTION AT REAR OF HELMET
MICROPHONE AT MOUTH

Legend: 1. Loudspeaker at rear
        2. Loudspeaker at top
        3. Loudspeaker at right ear

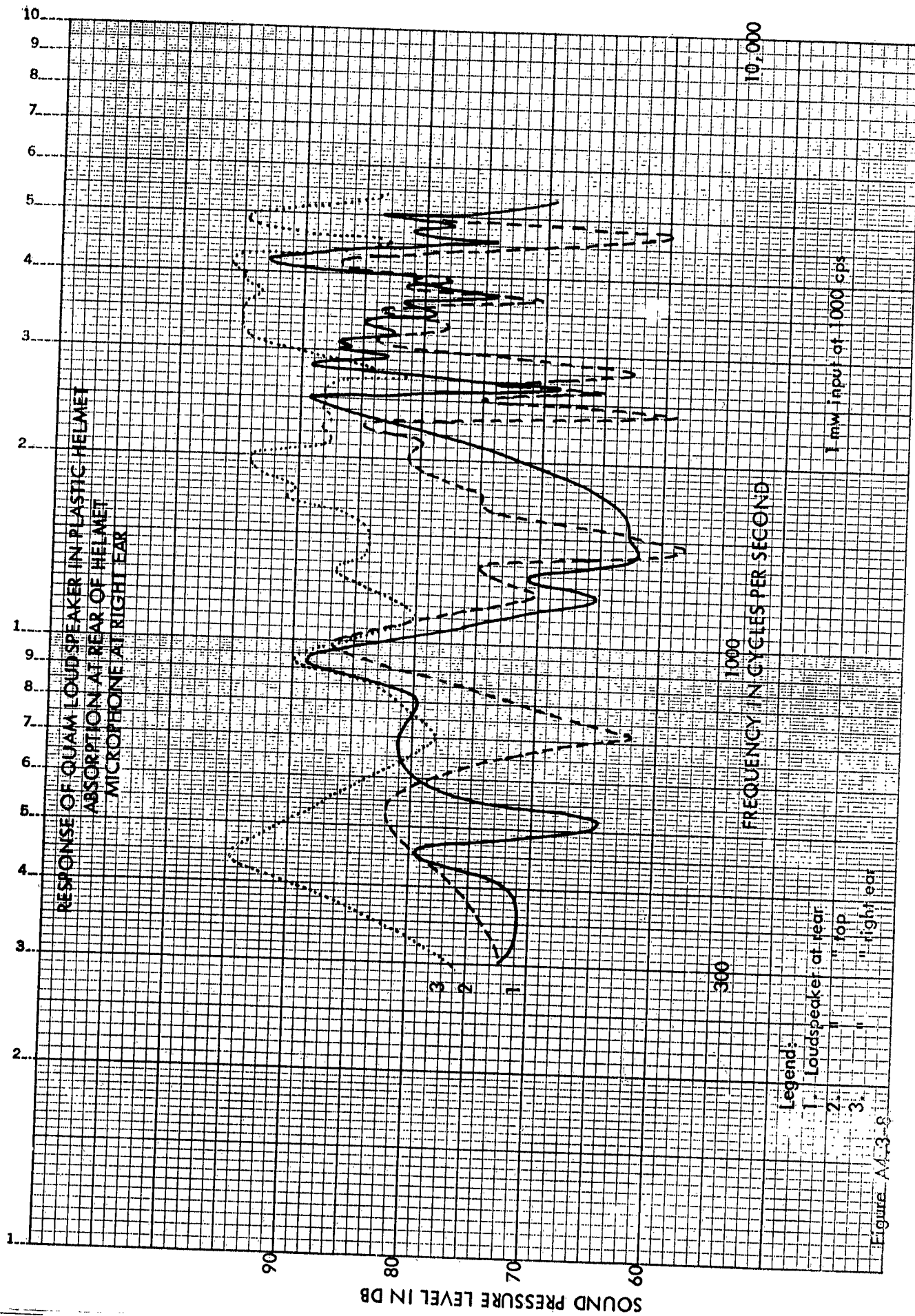SOUND PRESSURE LEVEL IN DB
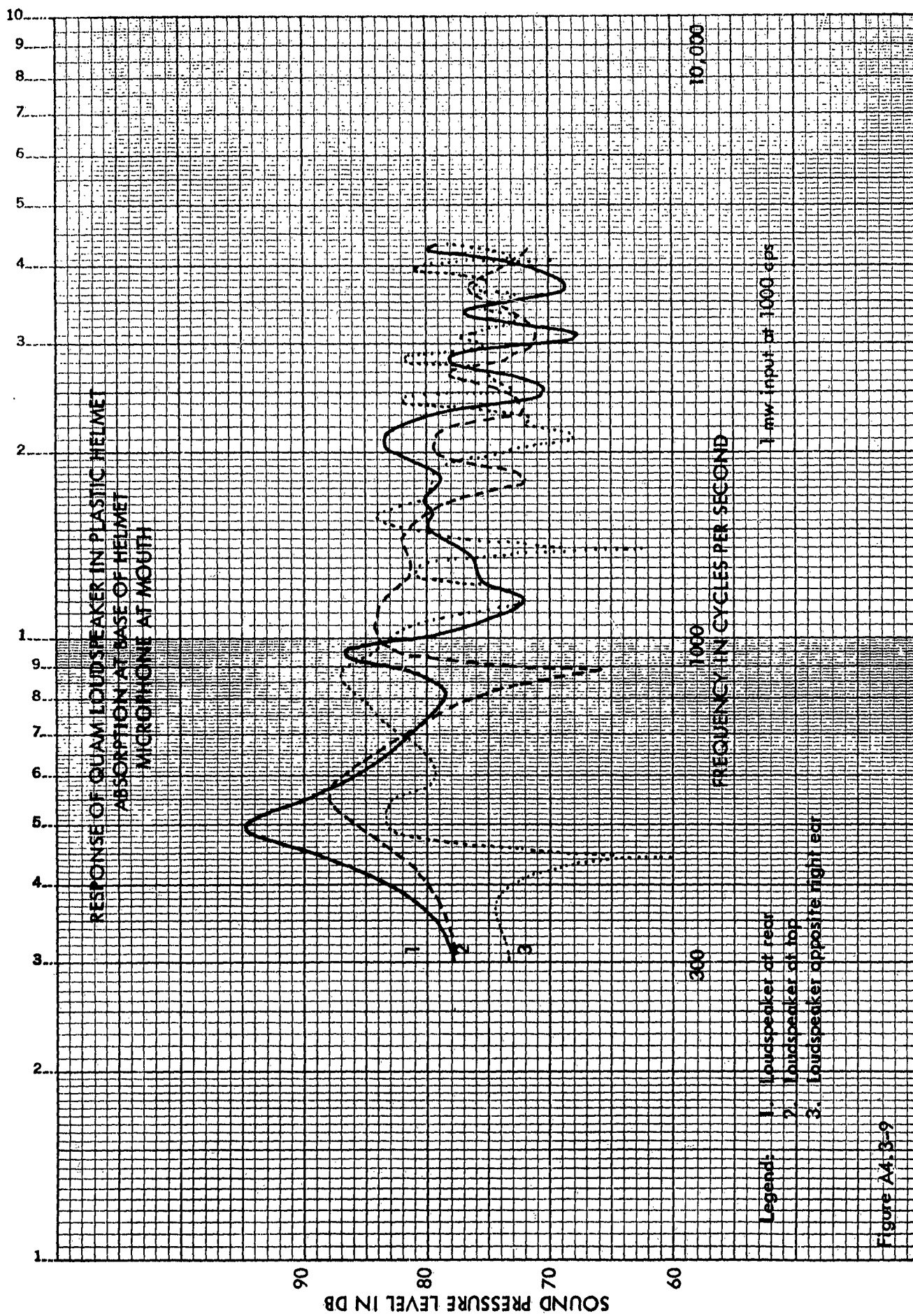
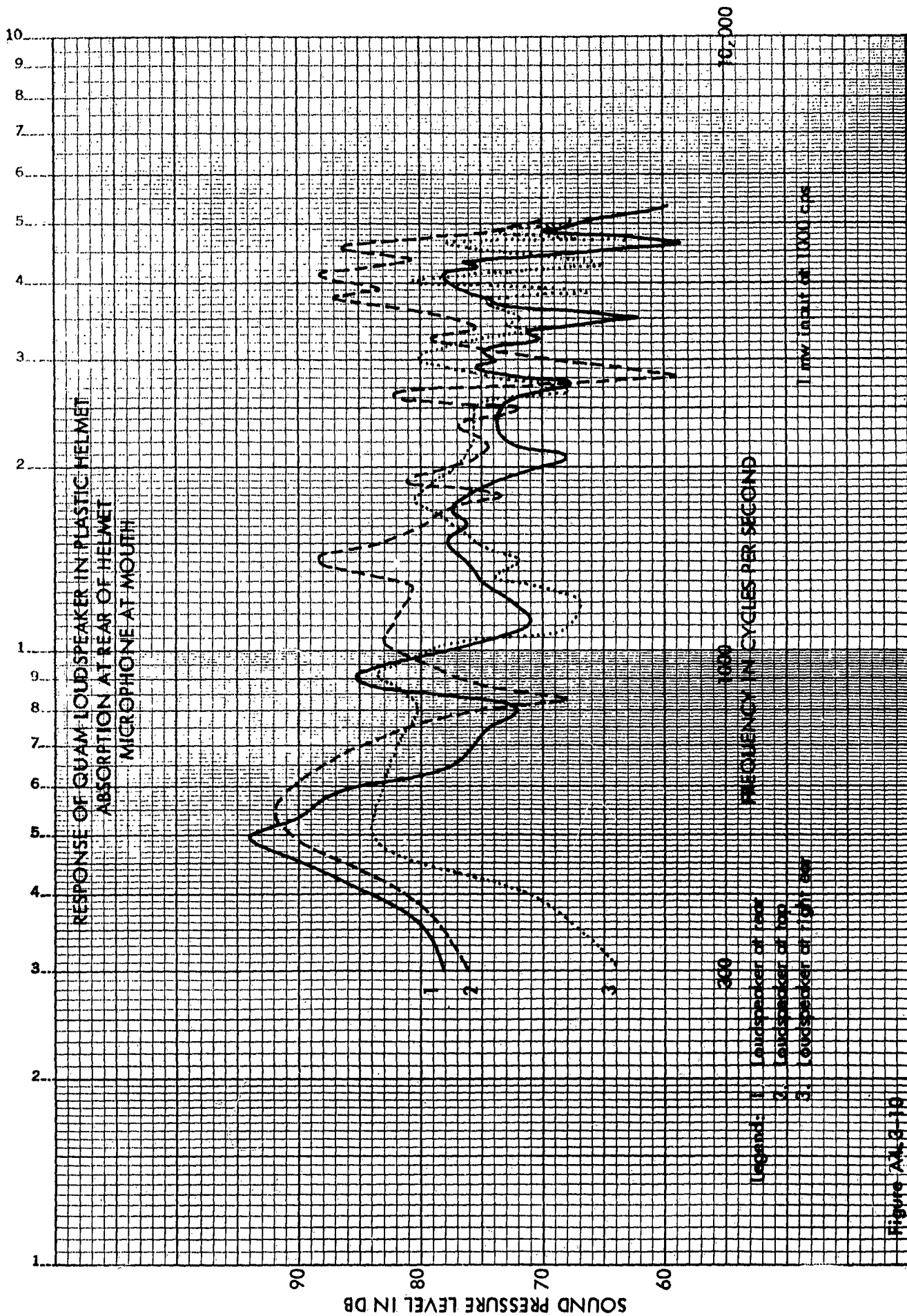FREQUENCY IN CYCLES PER SECOND

1 mw input at 1000 cps

Figure AXL3-19

TABLE I.

A. APPROXIMATE OVERALL SOUND PRESSURE LEVEL AT THE EAR FOR A POWER INPUT OF 1MW INTO HELMET LOUDSPEAKER

1. Absorption at Helmet Base

Loudspeaker Mounting Position	Power Input db re 1 watt	Approximate Overall Sound Pressure Level
Rear	-30	80
Top	-30	85
Opposite Ear	-30	90

2. Absorption at Helmet Rear

Rear	-30	78
Top	-30	77
Opposite Ear	-30	87

B. POWER REQUIREMENT TO ACHIEVE O DB S/N RATIO. 120 DB JN EXTERIOR TO HELMET. 30 DB HELMET ATTENUATION ASSUMED. *

| Loudspeaker Position	Absorption Position	Power Required (db re 1 watt)
Rear	Base	-20
	Rear	-18
Top	Base	-25
	Rear	-17
Opposite ear	Base	-27
	Rear	-30

* Long-time average power

4.4 Miniature Receivers in a Semi-Insert Ear Protector

Under Contract AF33(616)-3048, Western Electro-Acoustic Laboratory developed a semi-insert aural protective device. It is shown in Figure 1. Preliminary studies indicate that one size will fit approximately 85% of the adult male population. Comfort prospects are good.

The plug affords approximately 23 db attenuation below 1000 cps and 27 db attenuation above 1000 cps. The real ear attenuation as performed according to specification Z24.22/406 is shown in Figure

A small hearing-aid type receiver may be fitted on the plug with a special adaptor. The frequency response of the Dyna Empire Model D-58 fitted into the WEAL plug on a 2 cc coupler is shown in Figure 2. The receiver which is of the magnetic type, has a nominal impedance of 10 ohms. The receivers are directly usable with the AIC-10 equipment.

This earplug-receiver combination was used with two microphone systems in the articulation testing program. With a reasonable signal-to-noise ratio in the microphone channel, the earplug-receiver will yield close to 100% intelligibility in a 120 db jet noise spectrum.
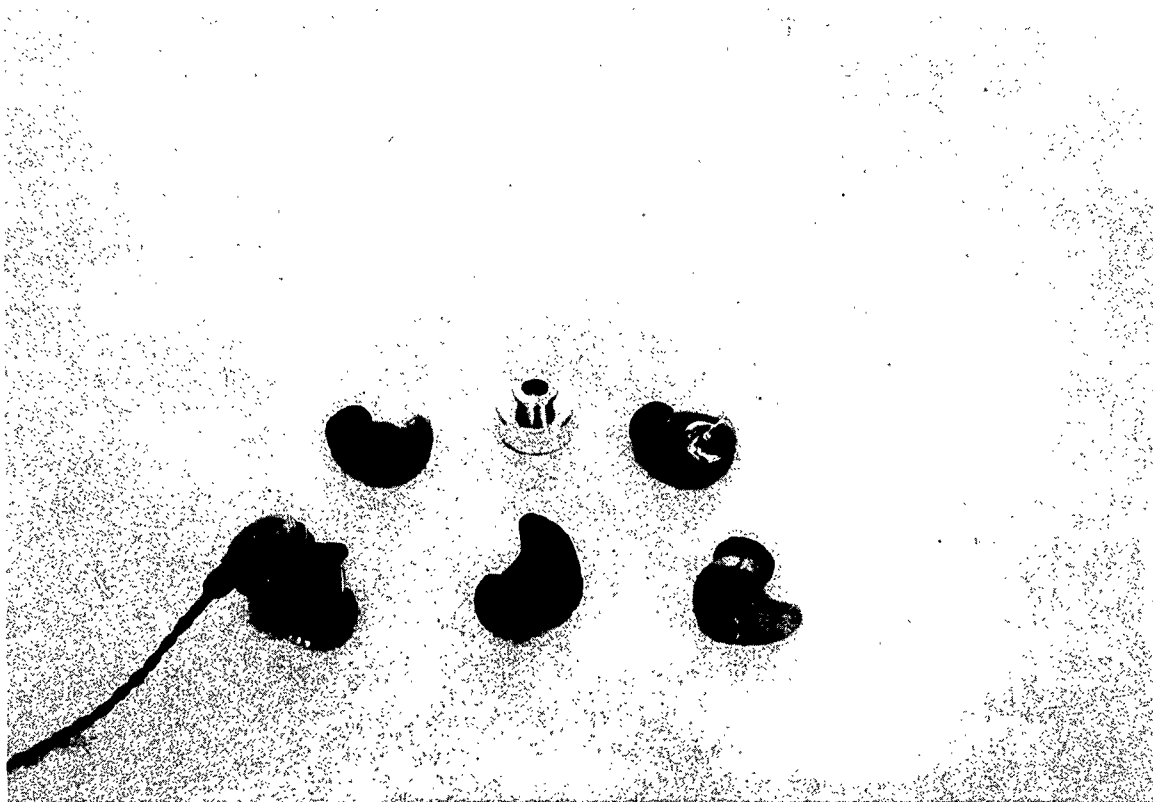
PHOTOGRAPH OF SEMI-INSERT DEVICE

Figure A4.4-1
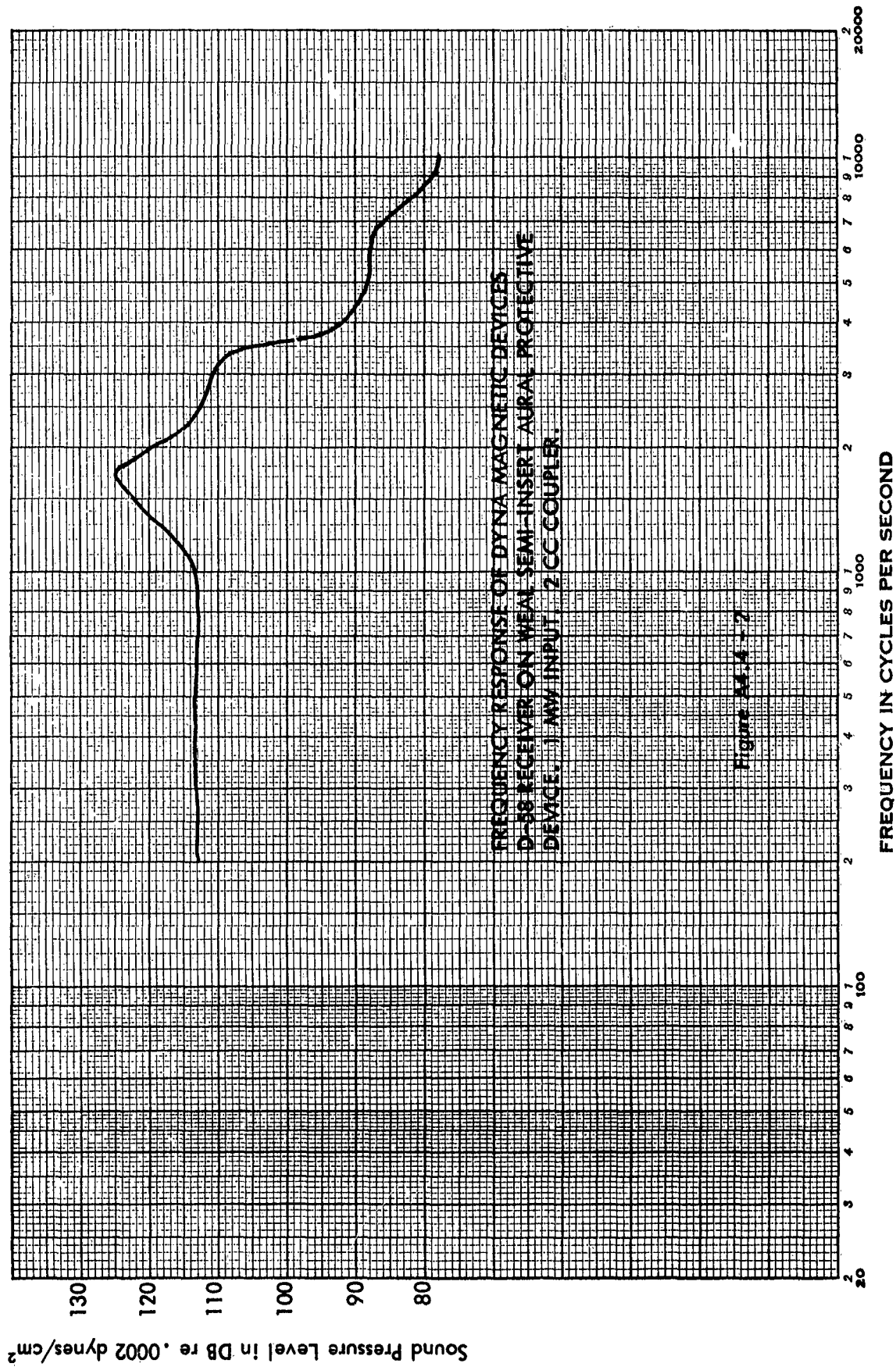
FREQUENCY RESPONSE OF DYNA MAGNETIC DEVICES
D-38 RECEIVER ON MEAL SEMI-INSERT AURAL PROTECTIVE
DEVICE. 1 MW INPUT. 2 CC COUPLER.

Figure A4.4 - 7

FREQUENCY IN CYCLES PER SECOND

Sound Pressure Level in DB re .0002 dynes/cm²

ATTENUATION OF WEAL SEMI-INSERT AURAL
PROTECTIVE DEVICE WITH MINIATURE RECEIVER
ATTACHED.

Average is result of 3 tests on
each of 10 individuals. Vertical
bars indicate spread of results.

FREQUENCY IN CYCLES PER SECOND

Figure A4.4 – 3

Attenuation in decibels
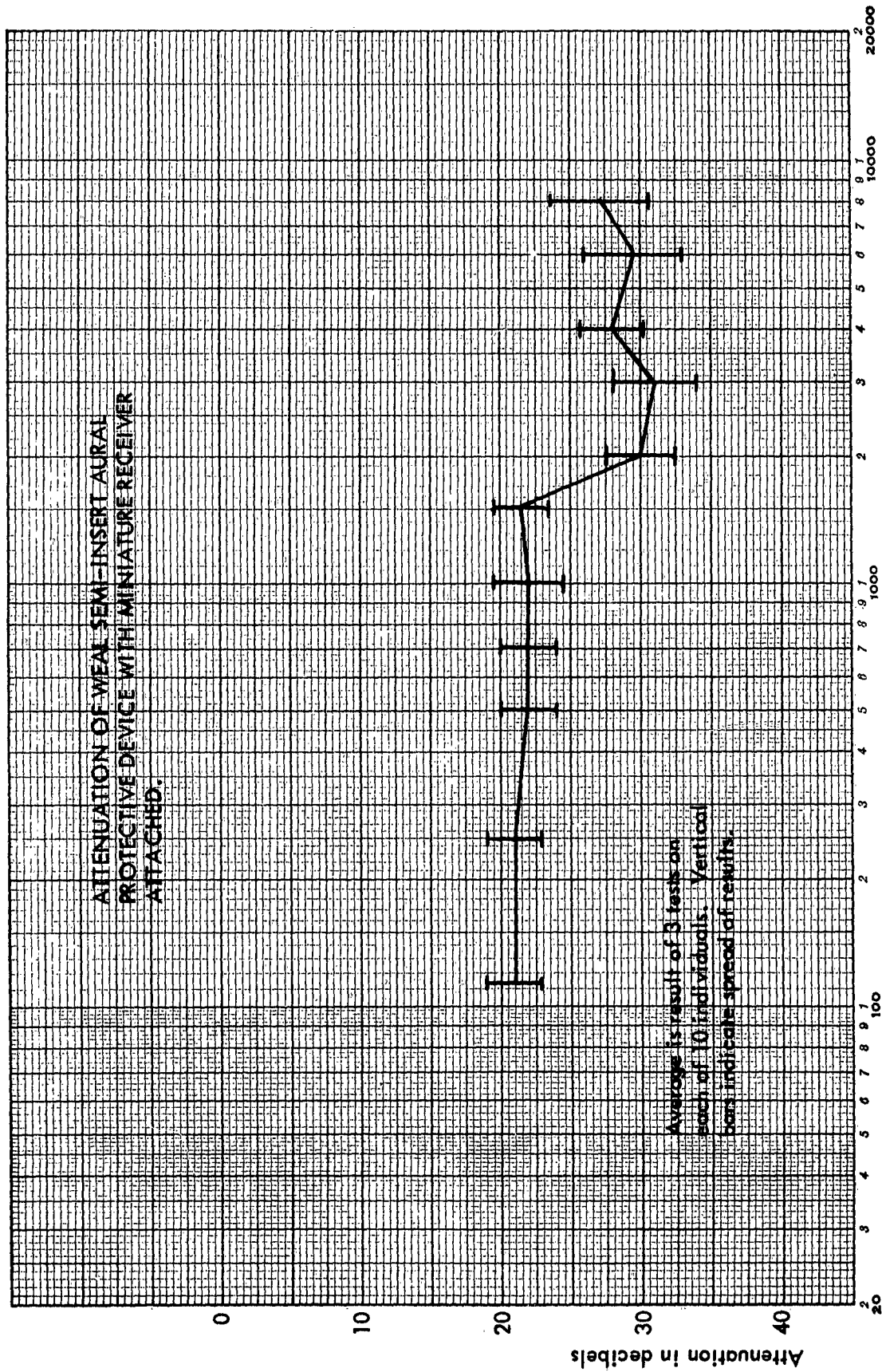
APPENDIX 5

ACOUSTIC FEEDBACK

5.1 SUMMARY

A generalized procedure for studying acoustic feedback has been developed. A technique for determing the signal-to-noise ratio at the ear as a function of frequency in terms of system parameters has been derived. These parameters can be measured separately in order to analyze the possibility of improvement where acoustic feedback is limiting the performance of a communication system.

5.2.0 GENERAL ANALYSIS OF FEEDBACK PROBLEM
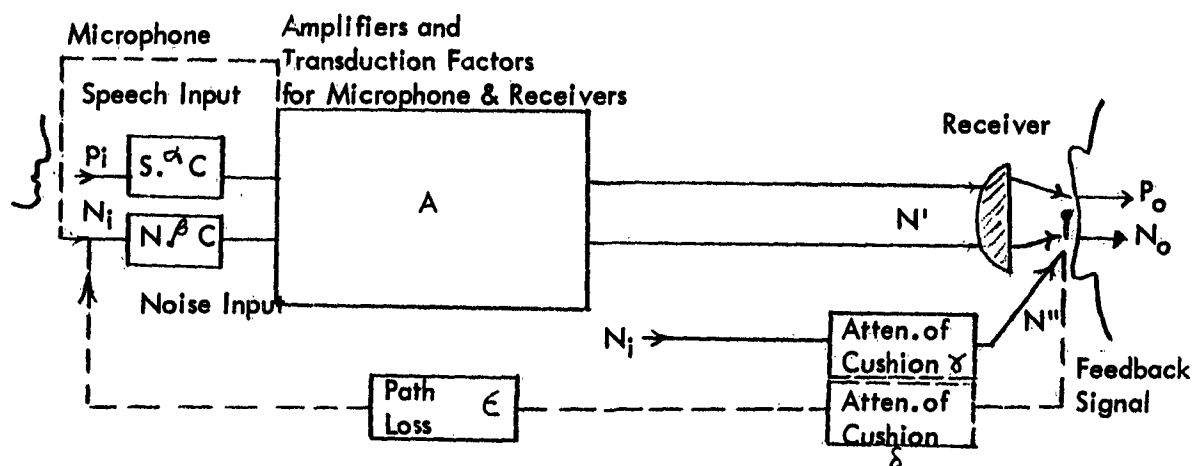
P_i = Speech Input (as measured by pressure microphone) at lips

N_i = Noise Input (as measured by pressure microphone) at lips or outside ear

P_o = Speech Signal Reaching Ear

N_o = Total Noise Reaching Ear

N' = Noise from Microphone Reaching Ear

N'' = Noise from Outside Reaching Ear Under Cushions

A = Gain Including Amplifiers and Transduction Factors for Microphone and Receiver

α = Speech Cancellation Fraction

β = Noise Cancellation Fraction

γ = Fraction of Noise Reaching Ear from Outside Cushion

δ = Fraction of Signal Reaching Outside from Under Cushion

ϵ = Path Loss Fraction

A5-1

DEFINITION OF SYMBOLS

P_i — Speech Input to Microphone as measured by an auxiliary pressure microphone. This quantity is not the speech in the microphone circuit but the speech at the microphone face.

N_i — Noise Input to Microphone or outside ear as measured by an auxiliary pressure microphone. Again, this is not the noise in the microphone circuit, but the noise at the microphone face.

P_o — Speech Signal reaching ear through microphone circuit.

N' — External noise reaching ear via microphone circuit.

N'' — External noise reaching ear directly (i.e. due to noise transmitted through ear protection devices).

N^o — Total noise reaching ear (i.e. $N' + N''$)

A — Acoustic gain of system. This quantity includes the electrical gain of amplifying equipment and the transduction factors of microphone and receiver units.

α — Speech cancellation fraction of microphone. $\alpha \begin{cases} > 0 \\ < 1 \end{cases}$ A measure of the discrimination of the microphone to a close source, i.e. speech. A pressure microphone has no speech cancellation; hence $\alpha = 1$; all speech transmitted.

β — Noise cancellation fraction of microphone. $\beta \begin{cases} > 0 \\ < 1 \end{cases}$ A measure of the discrimination of the microphone to a distant source, i.e. external noise. A pressure microphone has no noise cancellation; hence $\beta = 1$; all noise transmitted.

γ — Fraction of noise reaching ear from outside ear protection. $\gamma \begin{cases} > 0 \\ < 1 \end{cases}$ If γ were expressed in db it would refer to the real ear attenuation of the ear protector. For no ear protection $\gamma = 1$.

δ — Fraction of signal reaching outside from under ear protection. In general, $\delta = \gamma$ as defined above.

ϵ — Feedback path loss fraction. This is the fraction of the signal outside the ear protection which reaches the microphone. $\epsilon > 0$ and may be greater than 1 if a resonant condition prevails.

1. Derivation of Generalized S/N formula

The formula for the $(S/N)_{ear}$, i.e. the S/N ratio as perceived by the ear is derived as follows:

From the definitions the following relationships may be stated:

$$P_o = \alpha\, P_i\, A \qquad (1)$$

$$N' = \beta\, N_i\, A \qquad (2)$$

$$N'' = \gamma\, N_i \qquad (3)$$

$$N_o = N' + N'' = N_i(A\beta + \gamma) \qquad (4)$$

The $(S/N)_{ear}$ is $\dfrac{P_o}{N_o}$

$$(S/N)_{ear} = \frac{P_o}{N_o} = \frac{\alpha\, A}{A\beta + \gamma} \; \frac{P_i}{N_i} \qquad (5)$$

The value of A, the Acoustic Gain, is limited by acoustic feedback, as can be seen in the next section.

2. Derivation of $(S/N)_{ear}$ at the Feedback Frequency

The condition for feedback to occur is

$$L = A\bar{\beta} = 1 \qquad (6) \qquad \begin{array}{l} L = \text{open loop gain} \\ \underline{A} = \text{acoustic gain} \\ \bar{\beta} = \text{feedback fraction} \end{array}$$

Here $\bar{\beta} = \delta\epsilon\beta\,(7)$ ($\bar{\beta} = \delta\epsilon\alpha$ is not applicable because the returning speech signal, being a distant source, undergoes the same cancellation as noise)

Hence, combining (6) and (7) the maximum acoustic gain before feedback is

$$A = A_{max} = \frac{1}{\delta\epsilon\beta} \qquad (8)$$

Since in general the acoustic gain, which includes the transduction factors of microphone and receiver, is not constant with frequency, A will take on the value given in (8) only at the feedback frequency or frequencies designated $f_{f.b}$.

For example, suppose we have the following situation:
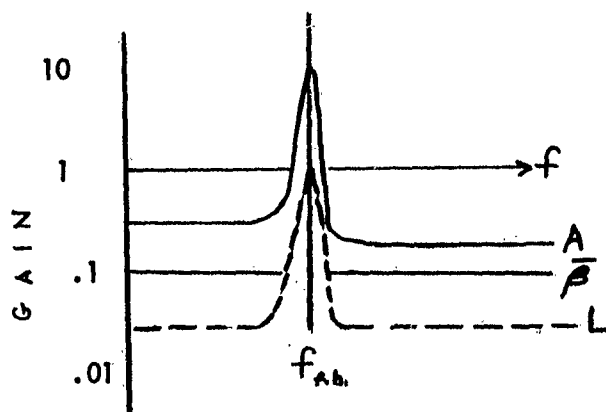
Before the feedback loop is closed, A could be raised or lowered uniformly depending upon the amount of electrical gain available. However, once the loop is closed, L cannot exceed 1. Hence, A is limited to the value shown above. The system feeds back at $f_{f.b.}$. At other frequencies $L < 1$ and hence, no feedback.

Combining (5) and (8) the maximum $(S/N)_{ear}$ as limited by feedback is:

$$\max(S/N)_{ear} = \frac{\alpha A_{max}}{\beta A_{max} + \gamma} \frac{P_i}{N_i} \qquad (9)$$

while the $(S/N)_{ear}$ at frequencies other than the feedback point is from (6)

at frequency $f \neq f_{f.b.}$

$$(10) \quad (S/N)_{ear}\bigg|_f = \frac{\alpha A}{\beta A + \gamma} \frac{P_i}{N_i}\bigg|_f \qquad \text{where all quantities are evaluated at frequency f.}$$

3. Formula for $_{max}(S/N)_{ear}$ in terms of system parameters:

Combining (8) and (9) 1

$$\max(S/N)_{ear} = \frac{\alpha}{\delta \epsilon \beta \left(\frac{\beta}{\delta \epsilon \beta} + \gamma\right)} \frac{P_i}{N_i} \qquad (11)$$

$$\max(S/N)_{ear} = \frac{\alpha}{\beta} \frac{1}{(1 + \delta \epsilon \gamma)} \frac{P_i}{N_i} \qquad (12)$$

the quantity $\left(\frac{P_i}{N_i}\right)$ is the (S/N) at the microphone face as measured by a pressure microphone. Assumes microphone at the lips. Call this $(S/N)_{lips}$

$$\therefore \max(S/N)_{ear} = \frac{\alpha}{\beta} \frac{1}{(1 + \delta \epsilon \gamma)} (S/N)_{lips} \qquad (13)$$

A5-4

The quantity $\frac{\alpha}{\beta}(S/N)_{lips}$ is the S/N in the microphone line or the S/N that a listener in a quiet room would have. Call this $(S/N)_{mic\ line}$

$$\therefore \max(S/N)_{ear} = \frac{1}{1 + \delta\epsilon\gamma}\ (S/N)_{mic\ line} \tag{14}$$

Both relations 13 and 14 are useful. One must remember that the quantity $\max(S/N)_{ear}$ applies only where

$$L = A\overline{\beta} = 1 \text{ (feedback frequency)}. \text{ At other frequencies the } (S/N)$$
must be computed by (10).

A5-5

TYPICAL SYSTEM	α β γ ϵ	Maximum $(S/N)_{ear}$ before feedback (In terms of $(S/N)_{lips}$)	Maximum $(S/N)_{ear}$ before feedback (In terms of $(S/N)_{mic\ line}$)	Maximum $(S/N)_{ear}$ before feedback as $\gamma \to 0$ (In terms of $(S/N)_{mic\ line}$)
1. Pressure mic., no ear protection	/ / / /	$\frac{1}{2}$ $(S/N)_{lips}$	$\frac{1}{2}$ $(S/N)_{mic\ line}$	$\frac{1}{2}$ $(S/N)_{mic\ line}$
2. Pressure mic., no ear protection, feedback path atten. important	/ / / ϵ	$\frac{1}{1+\epsilon}$ $(S/N)_{lips}$	$\frac{1}{1+\epsilon}(S/N)_{mic\ line}$	$\frac{1}{1+\epsilon}$ $(S/N)_{mic\ line}$
3. Noise cancelling mic., no ear protection	α β / /	$\frac{\alpha}{2\beta}$ $(S/N)_{lips}$	$\frac{1}{2}$ $(S/N)_{mic\ line}$	$\frac{1}{2}$ $(S/N)_{mic\ line}$
4. Noise cancelling mic., no ear protection, feedback path atten. important	α β / ϵ	$\frac{\alpha}{\beta(1+\epsilon)}$ $(S/N)_{lips}$	$\frac{1}{1+\epsilon}$ $(S/N)_{mic\ line}$	$\frac{1}{1+\epsilon}$ $(S/N)_{mic\ line}$
5. Pressure microphone, ear protection	/ / γ /	$\frac{1}{1+\gamma^2}$ $(S/N)_{lips}$	$\frac{1}{1+\gamma^2}$ $(S/N)_{mic\ line}$	$(S/N)_{mic\ line}$
6. Pressure mic., ear protection, feedback path atten. important	/ / γ ϵ	$\frac{1}{1+\gamma^2\epsilon}$ $(S/N)_{lips}$	$\frac{1}{1+\gamma^2\epsilon}$ $(S/N)_{mic\ line}$	$(S/N)_{mic\ line}$
7. Noise cancelling microphone. Ear protection.	α β γ /	$\frac{\alpha}{\beta(1+\gamma^2)}$ $(S/N)_{lips}$	$\frac{1}{1+\gamma^2}$ $(S/N)_{mic\ line}$	$(S/N)_{mic\ line}$
8. Noise cancelling mic., ear protection, feedback path important	α β γ ϵ	$\frac{\alpha}{\beta(1+\gamma^2\epsilon)}$ $(S/N)_{lips}$	$\frac{1}{1+\gamma^2\epsilon}(S/N)_{mic\ line}$	$(S/N)_{mic\ line}$

5.3 GENERAL CONCLUSIONS

Range of $\max(S/N)_{ear}$ based on preceding chart

The maximum $(S/N)_{ear}$ is found in item #7. As $\gamma \to 0$ (ear protection increases), the $\max(S/N)_{ear} \to (S/N)_{mic\ line}$. This figure can never be exceeded. This is a seemingly obvious conclusion; however, at first glance one might think that by increasing the gain higher and higher a large positive $(S/N)_{ear}$ could be achieved.

Therefore, it is useful to express the $\max(S/N)_{ear}$ in terms of $(S/N)_{mic\ line}$, realizing that this figure is the maximum obtainable.

The minimum $\max(S/N)_{ear}$ as limited by feedback is shown in (2). This figure will depend upon the feedback path fraction ϵ. In a resonant condition $\epsilon \gg 1$, the $\max(S/N)$ may be $\ll (S/N)_{mic\ line}$.

Effect of cushion attenuation (γ) on feedback problem

Comparing items (1) and (5), (3) and (7) on the chart, we find that adding ear protection will only increase the $\max(S/N)_{ear}$ by 3 db. In examples such as (6) and (8) where the feedback path fraction $\epsilon \gg 1$, a small amount of ear protection will serve to cancel the effect of the path.

At frequencies other than the feedback frequencies, the effect of γ is as follows:

from (10) $(S/N)_{ear}\Big|_f = \dfrac{\alpha A}{\beta A + \gamma} \cdot \dfrac{P_i}{N_i} = \dfrac{\alpha A}{\beta A + \gamma}(S/N)_{lips}$

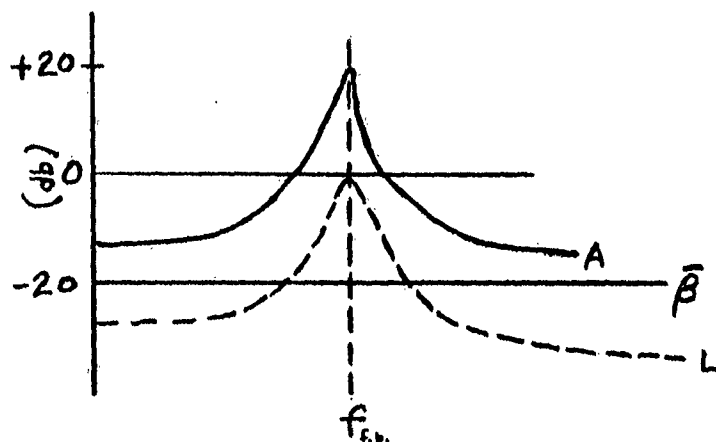Let us first assume that $\alpha = \beta = 1$ (pressure microphone)

$(S/N)_{ear}\Big|_f = \dfrac{A}{A+\gamma}(S/N)_{lips} = \dfrac{A}{A+\gamma}(S/N)_{mic\ line}$

If $A \gg \gamma$, $\dfrac{A}{A+\gamma} = 1$ and $(S/N)_{ear}\Big|_f = (S/N)_{mic\ line}$

If $A \ll \gamma$, $\dfrac{A}{A+\gamma} = \dfrac{A}{\gamma}$ and $(S/N)_{ear}\Big|_f = \dfrac{A}{\gamma}(S/N)_{mic\ line}$

Problem of $(S/N)_{ear}$ as a function of frequency

The analysis was based on $L = A\bar{\beta} = 1$ at the feedback frequency. For example, if $L, A, \bar{\beta}$ are in db, assume following:

Here the system feeds back at f

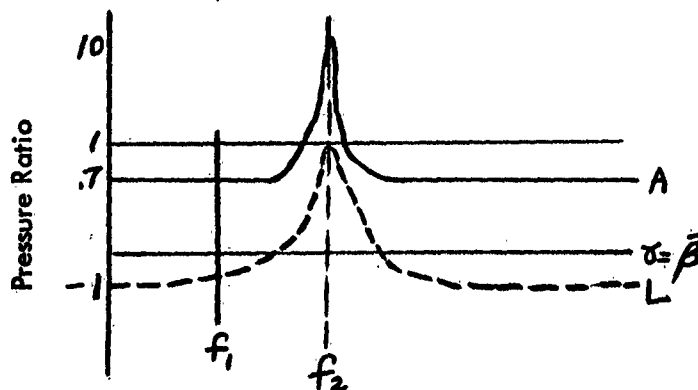Since $(S/N)_{ear} = \dfrac{\alpha A}{(A\beta + \gamma)} \dfrac{P_i}{N_i}$

only at frequency $f_{f.b.}$ can the substitution $L = A\bar{\beta} = 1 = A\,\beta\,\epsilon\,\delta$ be legitimately made.

At other frequencies $(S/N)_{ear} = \dfrac{\alpha\,A(f)}{(\beta A(f) + \gamma)} \dfrac{P_i}{N_i}$

where $A(f)$ indicates A as a function of frequency.

The extremes of this problem may be seen in the following two examples:

(1) Pressure Mic., $\alpha \neq \beta = 1$ Let $\epsilon = 1$. Assume $\gamma = .1$ Acoustic gain as shown below:

At feedback frequency f_2, $(S/N)_{ear} = \dfrac{10}{10 + .1}(S/N)_{lips} \approx 1(S/N)_{lips}$

At f_1, $(S/N)_{ear} = \dfrac{.7}{.7 + .1} = .87(S/N)_{lips}$

$\therefore$ even though there is a variation in acoustic gain of 20 db, the $(S/N)_{ear}$ is essentially $(S/N)_{lips}$ over a wide frequency range.

(2) Same as above, but $\gamma = 1$ (no ear protection)
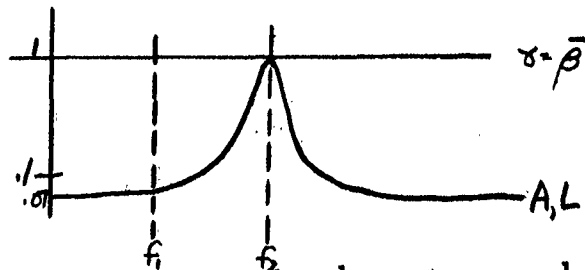
at f_r $(S/N)_{ear} = \dfrac{1}{1+1}\ (S/N)_{lips} = \dfrac{1}{2}\ (S/N)_{lips}$

at f_1 $(S/N)\quad = \dfrac{.07}{1+.07}\ (S/N)_{lips} = .07(S/N)_{lips}$

$\therefore$ there is about 20 db difference in $(S/N)_{ear}$ betweem 2 freq.

Two conclusions may be drawn from these examples:

(1) The Acoustic Gain, A, should be as constant with frequency as possible. In this way the maximum $(S/N)_{ear}$ could be obtainable at all frequencies.

(2) If the Acoustic Gain is not constant, then adequate ear protection must be used in order that the $(S/N)_{ear}$ as a function of frequency will be adequate.

Naturally, where $\alpha, \beta, \epsilon, \neq 1$ the results are not as straightforward as in the examples, but the same conclusions are valid.

5.4 EXPERIMENTAL VERIFICATION OF FEEDBACK THEORY

The experimental apparatus is shown in Figure 1. It was convenient to place the oscillator in the middle of the loop rather than in series with the microphone. The gain A2 was adjusted until the system fed back. The loop was then opened as shown in Part II of Figure 1. The open loop gain was then measured as a function of frequency as shown in Figure 2. Only at the feedback frequency (loop closed) did the open loop gain = 1 (equal in phase and magnitude). Also of interest is the gain of the system with feedback. This was measured for a gain 0.1 and 2 db below the feedback point and is shown in Figure 3. Since $A' = A/1-A$ where A' is the gain with feedback, $A' \to \infty$ as $A\beta \to 1$. Hence, A' is largest at the feedback frequency.

I. Physical Setup
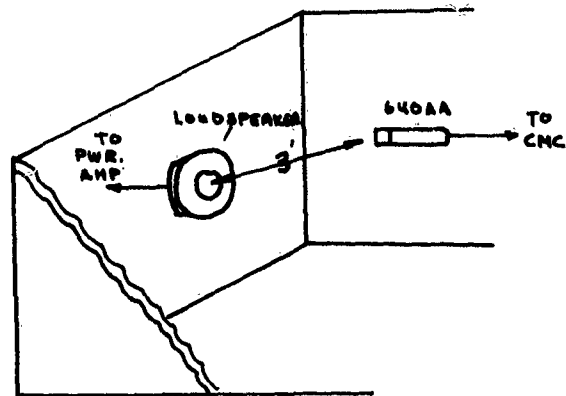
II. Measurement of Acoustic Open Loop Gain

Open Loop Gain = $L = \dfrac{E_o}{E_i}$
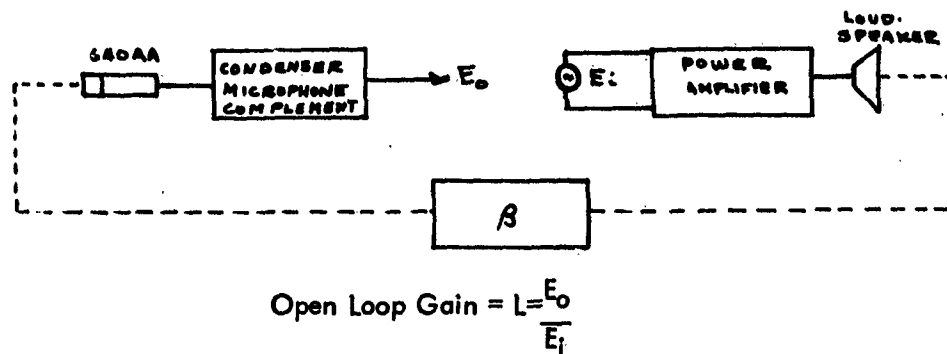
III. Measurement of Gain with Feedback

Gain with Feedback = $A^1 = \dfrac{E_o}{E_i}$

Figure A5.4-1

LOOP GAIN WITH FEEDBACK
SYSTEM: 640AA Microphone — Univ. MM-2 Loudspeaker in Quiet Room

Feedback Frequency

Measured 1 db below sing point
indicate value to which gain is reduced
when 2 db below sing point

Gain with Feedback

FREQUENCY IN CYCLES PER SECOND

FIGURE A5.4-7

OPEN LOOP GAIN AS FUNCTION OF FREQUENCY
SYSTEM: 640AA Microphone and Univeral MM-2 Loudspeaker in quiet room

Feedback Frequency

Note: The electrical gain was adjusted so that feedback just occured when loop was closed

FREQUENCY IN CYCLES PER SECOND

Open Loop Gain in DB

Figure A5.4-3

APPENDIX 6

MISCELLANEOUS STUDIES

6.1 Correlation of the Intelligibility of CVC Words and PB Words in Noise

In the exploratory phase of this program, a special list of CVC words was assembled for use in articulation studies. These words possess several advantages, especially that they require little or no learning period and provide a sensitive and efficient evaluation of a system's performance. However, heretofore most intelligibility tests have used PB words. Hence, in order to correlate our results with those found in the literature, a comparison of the intelligibility of CVC and PB words in noise was undertaken.

The results of this study are shown in Figure 1.

The testing apparatus is shown in Figure 2. The test material was recorded in a semi-anechoic room with a Western Electric 640AA microphone 1 ft. from the subject. The subject maintained a constant speaking effort, which was equivalent to 70 db at 1 ft.

When the recordings were played back the long time average of the test material determined the level of the signal. The long time average noise level was also determined. The output level of the tape recorder remained constant, while the noise level was changed by adjusting the attenuator. The spectrum shape of the masking noise is shown in Figure 3. This is essentially the same spectrum as the standard jet noise spectrum used throughout the contract.

6.2 Sentences Based on Air Force Vocabulary for Use in Intelligibility Testing

6.2.1 Purpose

In the final evaluation of a prototype communication system in noise, it is highly desirable that the evaluation be conducted under simulated field conditions. An important factor is therefore the choice of speech material for use in intelligibility testing. The use of word lists or the usual sentences is valuable in comparing systems and yielding engineering design parameters, but not typical of the communication which will be used over the proposed equipment. Therefore, a special list of sentences and phrases containing Air Force vocabulary typical of air-to-air, air-to-ground and ground-to-air communications has been assembled.

6.2.2 Source of Air Force Vocabulary

We requested word lists from Dr. Irwin Pollock of AFCRC, who referred our request to Ohio State Research Foundation. We have received several reports which contained suitable material.

A6-1

SENTENCE, PB WORD, AND CVC WORD
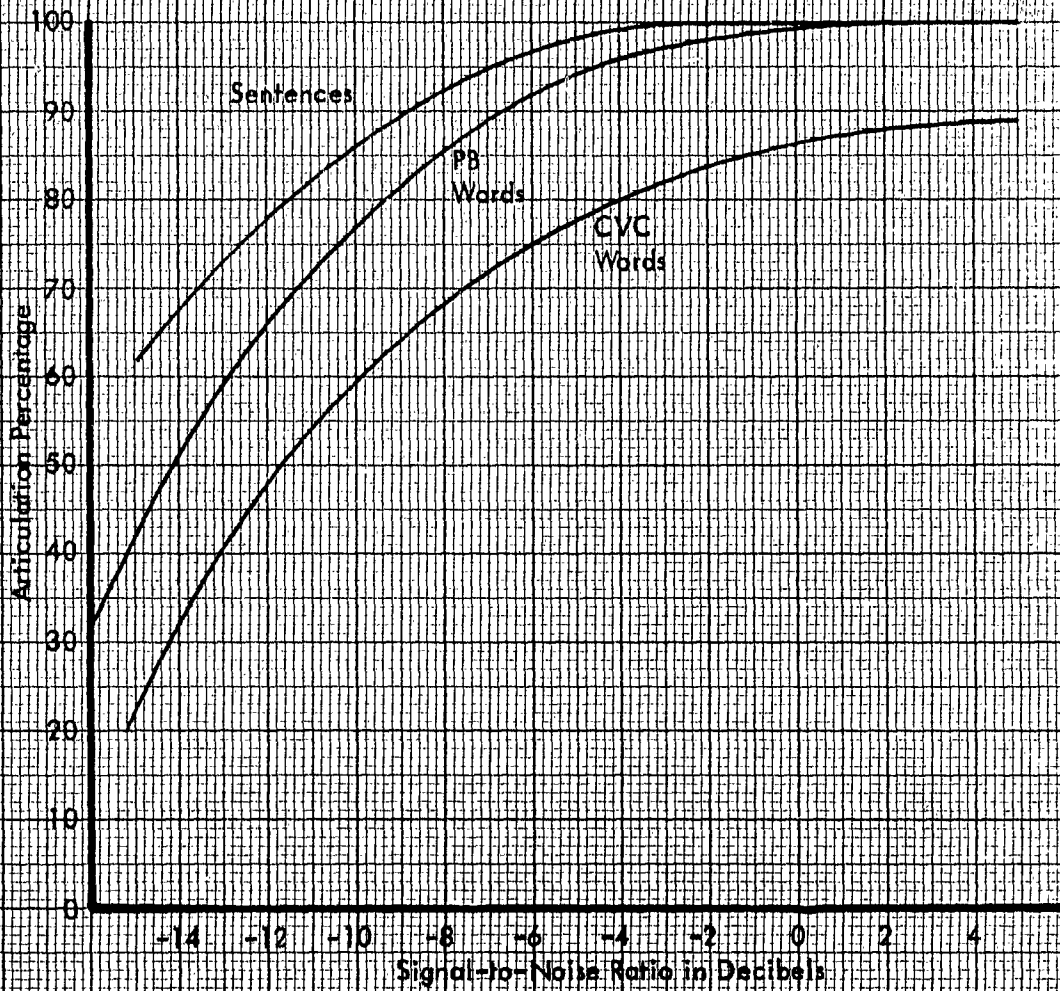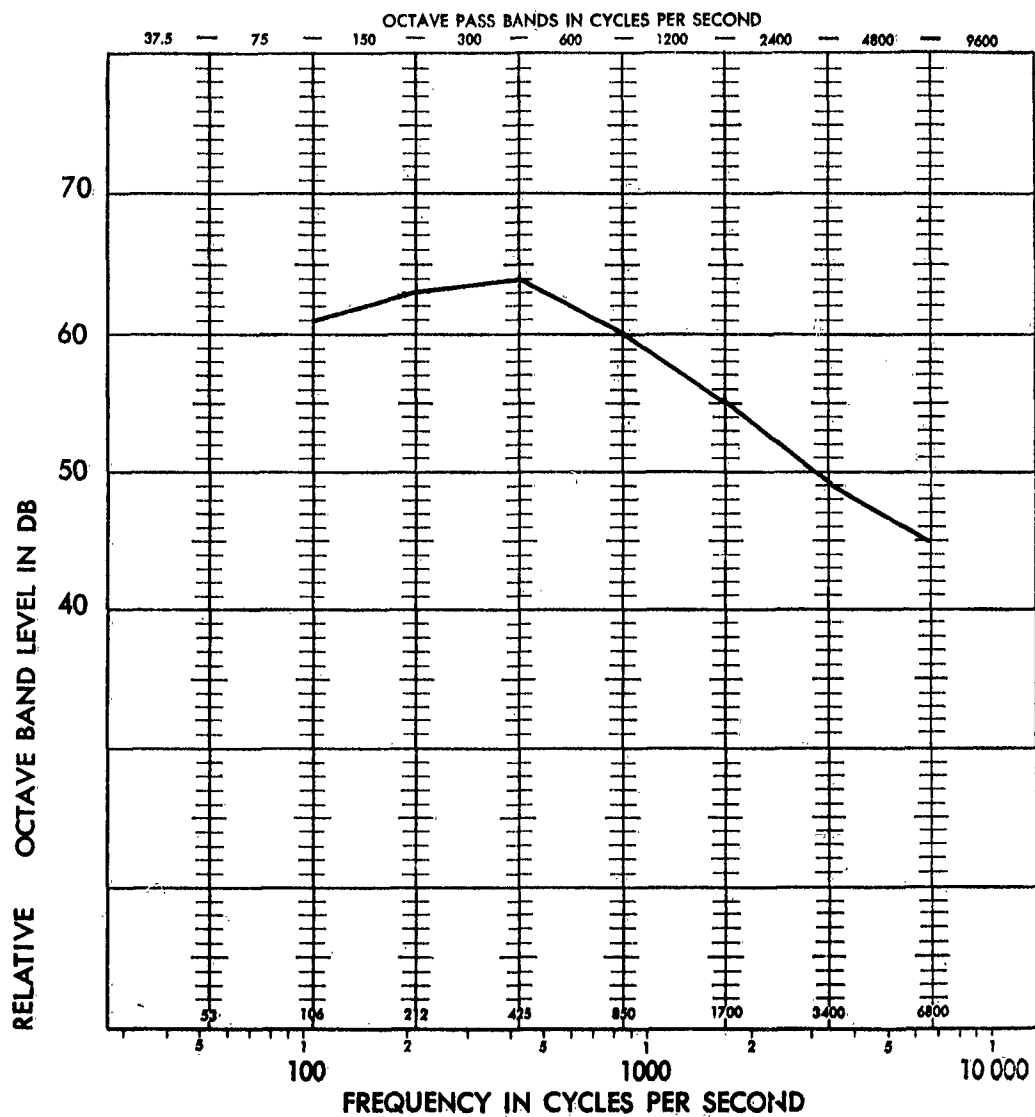ARTICULATION PERCENTAGE
VS SIGNAL-TO-NOISE RATIO

Figure A61-1

SPECTRUM OF MASKING NOISE USED IN CORRELATION OF THE
INTELLIGIBILITY OF CVC AND PB WORDS

This spectrum has approximately the same shape as
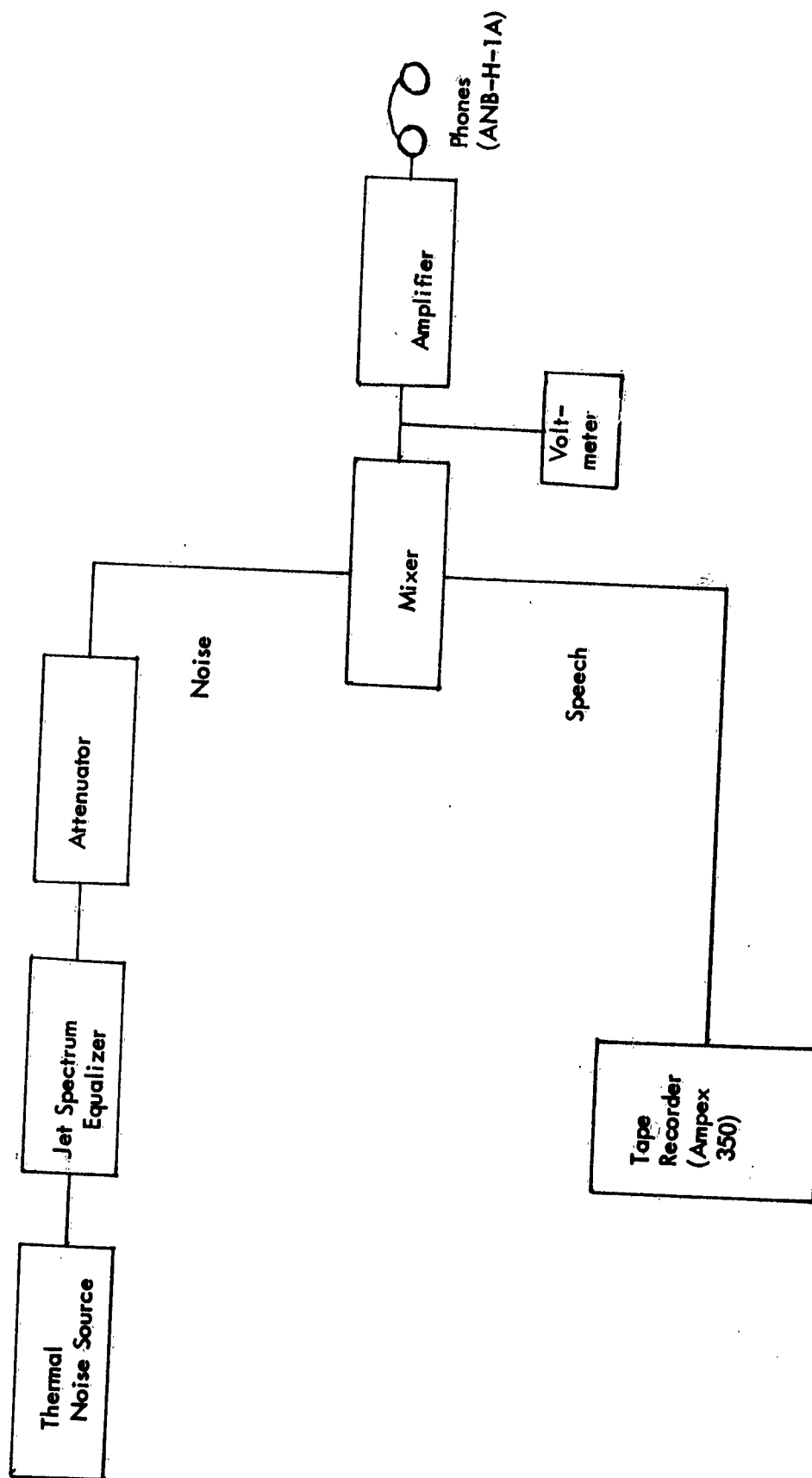120 db Jet Noise Test Spectrum used throughout the
program.

Figure A6.1-2

APPARATUS FOR MEASURING ARTICULATION SCORE VS SIGNAL-TO-NOISE RATIO

Figure A6.1-3

6.2.3 Design of Sentences Based on Air Force Vocabulary Which Will Stress Recognition and Minimize Memorization

The sentences and phrases based on the vocabulary described above were formed in such a way as to stress recognition of a limited vocabulary and to otherwise minimize rote and contextual memorization. In other words, the recognition of one word in the sentence will not furnish a clue to correct identification of other parts of the sentence, even though they are not perceived.

The sentences are formed in the following way: the vocabulary, placed on cards, is divided into three shuffled stacks: (1) initial words, i.e. words which ordinarily would begin a message, as "Roger," "Request," etc., (2) the body of the message such as "bearing 10° north," etc., (3) final words, such as "over," "out." The cards are then picked in order from the stacks and read; for example, "Roger, bearing 10° north. Over and out."

By shuffling and re-using the cards and changing the numbers involved, the permutations possible should eliminate any contextual memorization even with a limited vocabulary.

6.2.4 Training Period for Articulation Crew

The Testing Crew will be thoroughly familiar with the basic vocabulary and any standard procedure accompanying the words, as, for example, the fact that "bearing" is always accompanied by an angle and direction. Thus, we will truly be testing message intelligibility and not isolated words and phrases having no context.

6.3 Relation Between Peak, Long Time Average, and VU Peak Levels for Speech

Much confusion in the literature results when referring to signal-to-noise radio. The reason for this confusion is the manner in which the speech signal is measured. It is the purpose of this section to give relations between various techniques of measuring speech levels.

The sentence "Joe took father's shoe bench out, she was waiting at my lawn" was recorded by three male speakers using a normal conversational level. These tape recordings were later measured in three ways:

1. Long Time Average: The sentence was played back on a continuous loop and fed into a full-wave averaging voltmeter (measures but reads rms for nine waves) with a time constant of 3 seconds.
2. Peak Reading: The output of the tape recorder was displayed on an oscilloscope. The peak deflection was noted on a sine wave of known amplitude was adjusted

until its peak-to-peak deflection equalled the speech. Three decibels were then added to the sine wave.

3. Peak VU: The output of the tape recorder was fed into a standard VU meter. The peak deflection was noted over a long time.

Results: Taking 0 decibels as a reference level, the averaged results are

Long Time Average	0 db
VU Meter Peak	+8 db
Peak	+18 db

APPENDIX 6: THE LIMITS OF EAR PROTECTION

6.4-INTRODUCTION

Until recently it had always been our experience that if a listener receiving communication through headphones in a high noise field used earplugs under the receivers, the intelligibility of reception would be improved. Recently qualitative reports indicated a converse reaction when certain of the advanced types of muff protectors were used as earphone cushions.

At the meetings of the Acoustical Society in November, 1958 RCA personnel reported quantitative results from a series of tests using as earphone cushions their new large volume liquid sealed muff type protectors. Their report indicated that if the listener so equipped was exposed to a very high level noise field in which communication was marginal, and V-51 earplugs were inserted underneath the cushions, the intelligibility was decreased. Appropriate measurements of real ear attenuation furnished the proper quantitative clues to explain the phenomenon.

Heretofore, with older types of earphone cushions, we have always found that the attenuation furnished by the combination of cushion plus earplug was greater than the attenuation of the cushion alone. However, in the new RCA tests using their new muff type protector, for which the attenuation of the muff alone is as much as 40 db at 1000 cps, the insertion of the earplug actually decreases the attenuation. It will be recalled that the attenuation of the earplug alone is the order of 25 db at the same frequency. It was reported that the attenuation of the combination would be reduced as much as 10 db, as compared with the muff alone, i.e. to approximately 30 db.

This finding has implications both in regard to voice communication reception and in regard to the behavior of ear protectors as such.

In regard to communications, we are now alerted that we are approaching the maximum achievable ear protection and that the muff type protector has now been developed to the point where its attenuation not only exceeds that furnished by the best available earplug, but also that greater attenuation can no longer be achieved by the combination of protective devices.

In regard to ear protection, the implications are far more subtle and crucial. Serious consideration of the disclosure by RCA suggested that herein exists a means for demonstrating unmistakably a phenomenon which we had only deduced without direct

evidence during the various stages of our program for the development of a semi-insert type protector. In our progress report dated 16 October 1958 we stated the tentative conviction that we were achieving the maximum protection as limited by the vibration of the skull in the sound field, and we presented considerable indirect evidence to back this suspicion. In our Summary Report dated 28 February 1956 on Phase 1 of the program we discussed and diagrammed the theoretical behavior of earplug attenuation as determined by skull vibration in the frequency region of the primary skull resonance and also indicated a possible means for circumventing the resulting limitations, provided a sufficiently thorough study of the entire phenomenon were made possible. This discussion is appended to this report.

On returning from the meetings we resolved to repeat under idealized circumstances tests of the type that RCA had conducted in the hope of unmistakably verifying the principle we had postulated.

The reasoning proceeds as follows: First, we measure the attenuation of the semi-insert protector alone. Let us suppose hypothetically that in the region of skull resonance the attenuation is 20 db. Next, we measure the attenuation provided by a large circumaural protector. This device in our experiment is the massive, large volume unit described below. Precautions are taken that the coupling of the protector to the head is compliant, so that the vibration of skull as exposed to the sound field is not influenced by the protector, and also that the attenuation provided by the circumaural protector is as large as possible under the circumstances. Let us suppose that its attenuation is 35 db. Now, we reinsert the semi-insert protector under the circumaural protector and assume that the skull vibration remains unchanged. If under these circumstances the attenuation of the combination is greater than that of either protective device, we would have clear indication that the sound path is a pure airborne one, and that the protective devices are acting more or less independently. On the other hand, if the attenuation is precisely equal to that of the semi-insert device alone, then we could assume that the sound path to the hearing mechanism is completely bypassing the circumaural protective device and, in fact, that the performance of the semi-insert device is not being controlled by an external acoustic path, but rather by a path which also bypasses even the semi-insert device. Such a path might be described by the usual nonspecific term "bone conduction." We would feel then that the more specific explanation would be justified, namely that the semi-insert device, being protected from airborne acoustic exposure, is essentially standing still, that the skull is vibrating with respect to the almost stationary plug, and that this movement is generating pressure in the ear canal in just as real a sense as if the head were rigid and the closing device were vibrating in the usually supposed manner.

These tests have been carried out and are indeed most fascinating and illuminating, as described below.

6.5 DESCRIPTION OF EAR PROTECTORS EVALUATED

The real-ear attenuation of ear muffs alone, earplugs alone, and earplugs plus muffs was measured. The ear muffs consisted of steel tubes 25 cm long, 7.5 cm in diameter with a 3.1 mm wall thickness capped with a 1 cm thick steek disk. The tube was partially filled with Fiberglas. The large volume of 1100 cc insured that the bone conduction threshold was independent of the entrapped volume when the tubes were tested without earplugs. The tubes were coupled to the head by a compliant rubber ring and an airtight seal was assured by packing clay around the device. Large rubber bands supplied the necessary force to hold the device firmly to the head.

The earplugs evaluated with the tubes were the V-51R and the experimental semi-insert device, Model 19-S, under development by WEAL. The 19-S is fully described in progress report AF33(616)-3048 dated 16 October 1958.

6.6 RESULTS

The real-ear attenuations were measured in the WEAL soundproof room. All procedures conform to the proposed ASA standard. The following combinations were tested:

A. 1. V-51R only
    2. Tube only
    3. V-51R + tube

B. 1. 19-S only
    2. Tube only
    3. 19-S + tube

Three trained subjects took part in the tests. Results are shown in Figures 1 - 3. Two runs were made for each condition on each of the observers. Also tested on one subject was a commercially available ear cushion - the Willson Safe-T-Muff #258. These results are shown in Figure 4.

6.7 ANALYSIS OF RESULTS

The results of these tests display qualitatively the behavior which our theory has predicted. As usual, the most apparent feature is the variation among individuals, which we should expect to see.

The second feature we observe is that the attenuation of all devices, both individually and in combination, tends to be low in the region of 800 to 1500 CPS. Unfortunately, in the standard series of test frequencies only 1 KCPS occurs in this region, which has tended to obscure the phenomenon. Therefore, we have added 800 and 1500 CPS to the series for these tests.

More detailed analysis is assisted by color marking on the graphs.

It is of interest to ask two questions of the data:
1. How does insertion of the plug under the muff (tubes) alter the attenuation? The graphs are marked as follows: Frequency regions in which the attenuation is actually decreased when the plugs are added are shaded.   . Other frequencies for which the addition of the plugs increases the attenuation by no more than 5 db are marked by

solid bars. At all marked frequencies the insertion of the plug has either reduced the attenuation below that of the muff alone, or increased it by no more than 5 db.

The variation in the behavior between subjects is considerable. For the most part the anamolous behavior is in the range below 2000 CPS. The behavior is not significantly different between the V-51R earplug and the 19-S experimental plug, although the attenuation of the 19-S is in general slightly less than for the V-51.
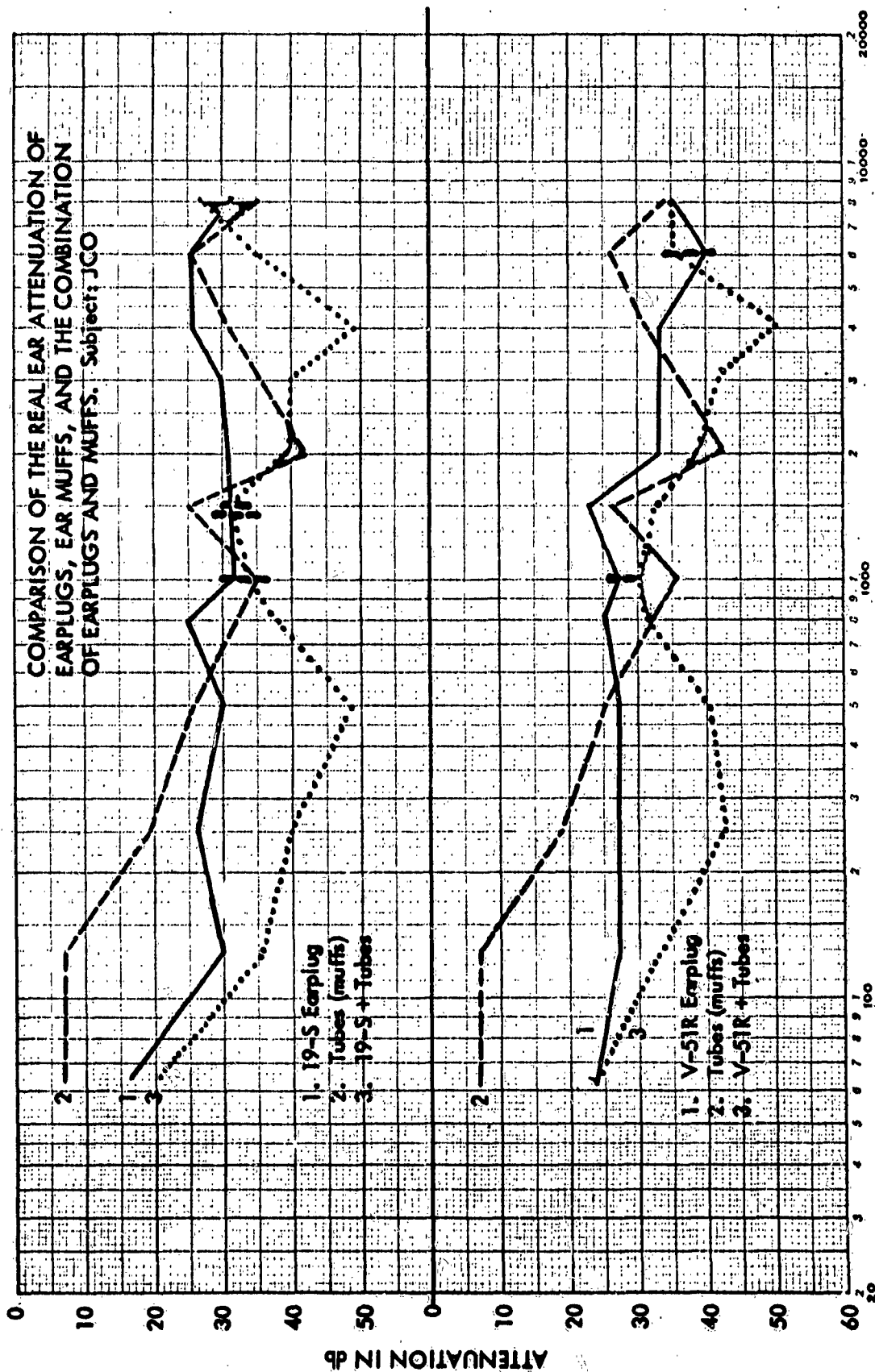
2. To what degree does the attenuation of the combination of muff plus plug approach that of the plug alone? The dashes indicate this proximity. For observers JCO and MG the muff gives no added attenuation to the 19-S alone at 1500 CPS. Again the anamolous behavior is mostly below 2000 CPS. This is the region in which the first flexural vibration mode of the skull is considered to occur (variously measured between 800 and 1600 CPS), and we have data to suspect that it may be quite variable among individuals.

Figure 4 shows the performance with a different muff protector; the results are qualitatively similar. It should be stressed that, in using the large steel tube muffs, we did not specifically seek maximum attenuation alone; rather, we sought first not to disturb the primary head vibration; hence, the use of a compliant coupling. The RCA tests were made with a better attenuator - characterized by light weight, rigid (liquid) coupling to the head, and large volume; but it would be difficult to say how these affect skull vibration. Evidently, using better muffs (not as yet available to us) the anamolous behavior is even more striking.

6.8 CONCLUSION

We believe, subject to further experimentation and discussion of correlated work with others, that these experiments strengthen the theory that the attenuation of aural protective devices is limited by the vibration of the skull in the sound field; that the limit will be most evident in the frequency region of the first flexural mode of skull vibration; that the limiting mechanism is the vibration of the skull with respect to a relatively immobile protector; that therefore the attenuation limit will be increased by making the protector as light in weight and large in volume as possible and by coupling it to the head over a large contact area and as rigidly as possible.

Unfortunately, it seems difficult to achieve these favorable factors with acceptable wearability in a small insert or semi-insert plug. The great advances in muff protection have been achieved by application of these principles, albeit unaware (apparently) of the behavioral phenomena herein recited.

COMPARISON OF THE REAL EAR ATTENUATION OF
EARPLUGS, EAR MUFFS, AND THE COMBINATION
OF EARPLUGS AND MUFFS.   Subject: JCO

FREQUENCY IN CYCLES PER SECOND

Figure A6.1-1

ATTENUATION IN db

1. 19-S Earplug
2. Tubes (muffs)
3. 19-S + Tubes

1. V-51R Earplug
2. Tubes (muffs)
3. V-51R + Tubes

COMPARISON OF THE REAL EAR ATTENUATION OF
EARPLUGS, EAR MUFFS, AND THE COMBINATION
OF EARPLUGS AND MUFFS.

Subject: JPC

1. 19-S Earplug
2. Tubes (muffs)
3. 19-S + Tubes

1. V-51R Earplug
2. Tubes (muffs)
3. V-51R + Tubes

ATTENUATION IN db

FREQUENCY IN CYCLES PER SECOND

Figure A6.1-2

COMPARISON OF THE REAL EAR ATTENUATION OF EARPLUGS, EAR MUFFS, AND THE COMBINATION OF EARPLUGS AND MUFFS.   Subject: MG

1. 19-S Earplug
2. Tubes (muffs)
3. 19-S + Tubes

1. V-51R Earplug
2. Tubes (muffs)
3. V-51R + Tubes

ATTENUATION IN db

FREQUENCY IN CYCLES PER SECOND
Figure A6:1-3

COMPARISON OF THE REAL EAR ATTENUATION OF EARPLUGS, EAR MUFFS, AND THE COMBINATION OF EARPLUGS AND MUFFS.

Subject: MG

Legend:

1. 19-S Earplug only
2. Willson #258 Muffs
3. 19-S + Willson Muffs

ATTENUATION IN db

FREQUENCY IN CYCLES PER SECOND

Figure A6.1-4